June 25

PRINCIPLES OF ELECTRIC MOTORS AND CONTROL

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FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK: 370 SEVENTH AVENUE
LONDON: 6 & 8 BOUVERIE ST., E. C. 4
1924

PRINTED IN THE UNITED STATES OF AMERICA

PRESS OF
BRAUNWORTH & CO.
BOOK MANUFACTURERS
BROOKLYN, N. Y.

PREFACE

Most existing texts dealing with electric motors and controllers treat the subject primarily from the design viewpoint. A much larger class is interested in the application and operation of this equipment than in its manufacture. Faulty application can nullify good design. The responsibility for selection of electrical equipment is widespread, as contrasted with its design by a comparative few. In view of these facts it seems desirable that information as to the principles, performance, characteristics and practical construction of electric motors and controllers be widely disseminated. This text is intended for students and for those interested in the selection, application, purchase, sale and use of electric motors and controllers and electric power.

The treatment is of simple and practical character and higher mathematics, vector diagrams and similar complications have been avoided. The motors described are those in regular commercial use. Theoretical types have been mentioned only where they have a bearing on practical designs. In the chapters devoted to controllers it has been the endeavor to set forth fundamental principles and to describe a sufficient number of actual units to illustrate the various principles and practices. The differing methods of the several designers are treated and the text is in no way confined to the apparatus or practice of any one manufacturer. The control diagrams have all been reduced to conform, so far as possible, with the standards of the Electric Power Club.

In this text the principles, construction and performance of electric motors and controllers have been treated. Specific applications are given mention only as they serve to illustrate the application of principles. In a companion volume "Electric Drive Practice" the subjects of selection and application of

motors and controllers are treated at length and the best practices in the application of electric drive equipment to specific machines and in prominent industries are stated. Many of the discussions and examples there given amplify and illustrate the principles set forth in this text.

As the contemporary literature on the subject of electric drives is widely scattered, bibliographies have been included to enable the reader to pursue further any individual line of investigation. The bibliographies are not intended to be complete but mention is made of some of the best references which are recent and easily accessible.

Much of the text has been published previously in the technical press. Such material has been extensively revised, enlarged and correlated. Acknowledgment is due the editors of the following magazines who have cooperated graciously:

Blast Furnace and Steel Plant,
Electrical Review (*Industrial Engineer*),
National Engineer,
Power,
Power Plant Engineering,
Railway Electrical Engineer,
Southern Engineer.

Acknowledgment is also due to many friends who have given valuable assistance and suggestions and who have kindly reviewed various portions of the manuscript. Particular mention is due to the following: S. H. Mortensen, Allis-Chalmers Mfg. Co.; Val. A. Fynn, Consulting Engineer; F. J. Burd and N. L. Mortensen, Cutler Hammer Mfg. Co; J. M. Hollister, J. I. Hull, John Liston and J. D. Wright, General Electric Co.; Theo. Schou, Ideal Elec. & Mfg. Co.; F. A. Annett, Associate Editor, *Power;* A. M. MacCutcheon, Reliance Elec. & Engineering Co.; P. V. Stewart and G. E. Stoltz, Westinghouse Elec. & Mfg. Co.

GORDON FOX.

CHICAGO, ILL.
December, 1923

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PRINCIPLES OF ELECTRIC MOTORS AND CONTROL

CHAPTER I

MOTOR ACTION

The Magnetic Field.—The underlying principles of electric motor action may be briefly explained in a manner comprehensible to the layman. The operation of all electric motors is based upon the relations existing between magnetic and electric circuits. Magnetism may be considered as lines of force which, in the ordinary magnetic circuit, follow a closed path through iron from south pole to north pole and through air from north pole to south pole. Magnetic materials possess high permeability or conductivity to the passage of these lines whereas non-magnetic materials possess low permeability. There is no insulator of magnetism. Figure 1 shows how magnetic lines are distributed in the space between the poles of a magnet.

Field about a Conductor.—A conductor through which an electric current is flowing is surrounded by a closed circuit of magnetic lines as shown in Fig. 2. The principle of the electro-magnet is at once evident. A number of turns of wire are placed about an iron core which will not retain permanent magnetism to any considerable extent. When a current is passed through the wire the magnetic fields of the individual turns act collectively to cause the major portion of the lines of force to pass through the central iron core and return through whatever magnetic circuit may offer the least resistance to the passage of the magnetic lines. Figure 3 illustrates how the magnetic influence of the individual turns combines to form

a strong resultant magnetism in the core. By changing the value of the electric current the strength of the magnetism is controlled. It is found that, up to a certain point, the strength

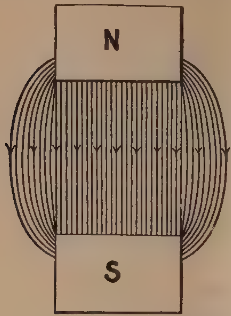

FIG. 1.—Magnetic field between the poles of a magnet.

FIG. 2.—Magnetic field around a wire carrying electric current. (Current flowing toward the reader).

of the magnetism in iron, measured by the number of lines in a given area, varies almost directly as the magnetizing current. Above this point a greater increase of current is required to

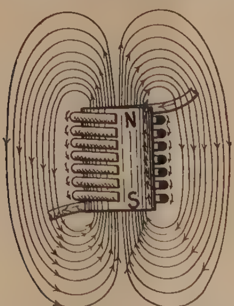

FIG. 3.—The electro-magnet, showing how magnetic lines of individual turns combine to form resultant field.

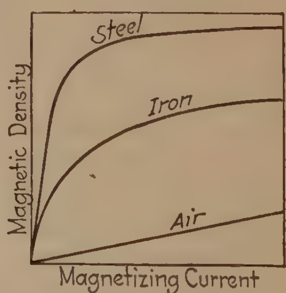

FIG. 4.—Magnetization curves of iron, steel and air.

cause an equal increase in magnetic density. This point is called the point of saturation and when iron is magnetized above this point it is said to be saturated. Air does not become saturated. Figure 4 gives magnetization curves for iron, steel and air.

Magnetic Reaction.—If a conductor carrying an electric current be placed in the field between two magnet poles, the magnetic lines of the main field and the field about the conductor will be superimposed. These lines will combine to form a resultant field as shown in Fig. 5, since the component lines of force are cumulative on one side of the conductor and opposing on the other side. The magnetic lines to the left of the wire tend to straighten out, acting similarly to elastic rubber bands and, in doing so, exert a sidewise force on the wire as indicated.

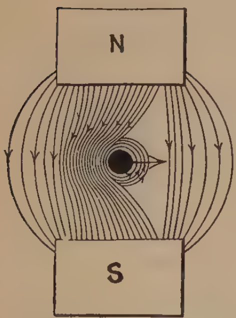

FIG. 5.—Resultant magnetic field due to wire carrying current placed in field under a magnet.

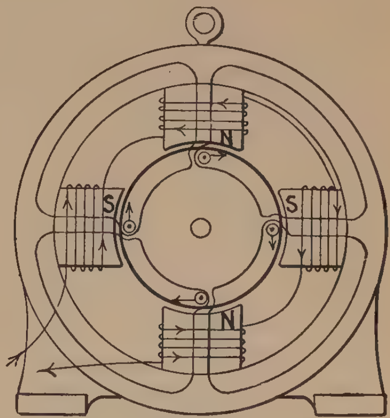

FIG. 6.—The principle of motor action.

Production of Torque.—All electric motors are fundamentally dependent upon this principle for their action. They consist of two members, one of which is arranged to rotate. There is a small clearance of air gap between the stationary and the rotating member. Currents flowing in the conductors of both members set up magnetic fields. The resulting main flux flows in closed magnetic circuits through both the stationary and rotating members and passes twice across the air gap between them. The currents in the conductors react with the magnetic fields to produce forces which, in the movable member, give rise to torque and rotation. Figure 6 illustrates the principle of motor action.

The rotative force or torque set up in a motor is caused by the reaction between magnetic fields and current-carrying conductors. The stronger the magnetic field the greater the sidewise force. Likewise, the higher the current in the conductor the more the field lines are distorted and the greater the mechanical influence upon the conductor. Obviously, the greater the number of like conductors the greater the total force. This leads to a basic law which applies to all electric motors. The mechanical force or torque exerted is proportional to the magnetic flux of the fields, the number of conductors and the electric current in the conductors situated in those fields and reacting with them.

Generation of Voltage.—If a conductor be moved across a magnetic field in such manner that the conductor cuts the magnetic lines, a voltage is generated in the conductor and a potential difference exists at its terminals. If the terminals be connected to form a closed circuit an electric current will flow in that circuit. If several conductors be connected together in series, the total voltage existing across the circuit terminals at any instant will be the algebraic sum of the voltages generated within the individual conductors at that instant. The value of the voltage generated in such a circuit is proportional to the strength of the magnetic field cut, the number of conductors in series and the rate at which the conductors are moved across the magnetic field. This is the fundamental principle of electric generator action.

Magnetic Induction.—When a conductor is placed in a magnetic field of varying strength, that is, a field in which the intensity or direction of the magnetism is made to change, an electric voltage is set up in the conductor. If the circuit be closed, a current will flow in it. This current tends to oppose the change of the magnetism. The greater the rate of change the greater the voltage and current induced in the conductor. Upon this principle the transformer is based. The alternating current induction motor also depends in part upon magnetic induction, hence its name.

CHAPTER II

THE DIRECT-CURRENT MOTOR

GENERAL ACTION

Basic Principles.—A current-carrying conductor, placed in a magnetic field, exerts a mechanical force. This principle is applied in a direct-current motor in the following manner: The motor frame comprises a stationary iron yoke carrying pole pieces projecting radially inwards. The poles are wound as electromagnets and furnish the main magnetic field. The rotating element, the armature, is a built-up drum carrying conductors through which current travels. The reaction of the current in the armature conductors upon the magnetic field results in a turning effort which rotates the drum.

Function of the Commutator.—The direction of the force exerted by a conductor depends upon the direction of the field magnetism and the direction of the current flow. The field poles of a motor are alternately north and south since the shortest paths for magnetic lines are afforded by this arrangement. As the drum rotates, a given conductor passes alternately under north and south poles. It is evident that, if the forces exerted are to remain continuously in one direction, the flow of current in the conductor must be in one direction when the conductor is under a north pole and in the other direction when it is under a south pole. The conductors on the armature of a direct-current motor are so connected that when they are midway between main poles the direction of current flow is reversed. It is this feature that enables the drum to rotate continuously in a single direction. In order to reverse periodically the current in the armature conductors, leads from them are brought out to a commutator. The use of a commutator makes possible the introduction of continuous current into the conductors with periodic reversals as above explained.

It is thus seen why a commutator is a necessary part of all direct-current motors.

Action of Counter-voltage.—Electric motor action is not alone involved in the working of a direct-current motor. Electric generator action also plays an important part. The action in a direct-current motor is as follows: The armature is subjected to approximately the full line voltage as its terminals are connected to the two line wires when in operation. The electrical resistance of the armature circuit is small. Current passing through the armature conductors reacts with the field magnetism to set the armature into rotation. As soon as the armature begins to rotate, its conductors begin to cut the magnetic lines emanating from the field poles. This process, following the laws of the electric generator, sets up in the armature conductors a voltage which is in opposition to the voltage of the supply circuit. As the motor increases its speed, this counter-voltage increases in value, but it cannot equal the impressed voltage. The motor attains such a speed that the counter-voltage is less than the impressed voltage by an amount such that the voltage difference is just sufficient to force through the resistance of the armature circuit a current sufficient to react with the field magnetism to produce a torque equal to the mechanical couple demanded by the external load. If the load increases the motor drops in speed slightly, the counter-voltage decreases and the voltage difference increases. A greater current is thus forced through the armature, producing sufficient torque to carry the increased load. The characteristic performance of all types of direct-current motors can be most readily understood if these facts are constantly borne in mind.

Determination of Speed.—The speed of a motor is governed by the fact that sufficient counter-voltage must be generated to restrict the current flow to an amount necessary to develop the required torque. The counter-voltage developed is proportional not only to the speed, but also to the number of conductors connected in series in the armature and the intensity of the field magnetism. If two armatures were operated in the same field frame, one built with twice as many turns in series as the other, then the first would rotate at half the speed of the

second because the necessary counter-voltage would be developed at the lower speed in the armature having more conductors in series. If a motor be operated at a given speed with the field magnetism at a given intensity and the intensity be decreased, then the motor will increase its speed. This is evident for it will be necessary for the armature conductors to pass the poles more rapidly in order to cut the same number of magnetic lines in a given time and maintain approximately the same counter-voltage. The various speed characteristics obtained with direct-current motors all depend fundamentally upon the relations of speed to counter-voltage and counter-voltage to field magnetism.

Direct-current motors are ordinarily classified as being shunt-wound, series-wound or compound-wound. This classification is based upon the method of connecting the field magnet coils. It may be repeated that the speed and torque characteristics are directly dependent upon the field intensity. If this intensity is made to vary in different ways the characteristics of the motor are controlled in a corresponding degree. The several types of direct-current motors will be considered individually.

SHUNT-WOUND MOTORS

Principles of Action.—In a simple shunt-wound motor the terminals of the field circuit are connected directly across the line as in Fig. 7. The field coils are subjected to line voltage, the current in them is nearly constant and is independent of the armature current. Since the field ampere-turns are nearly constant, the flux intensity remains approximately constant regardless of the load upon the machine and the current in the armature. The armature terminals of a shunt-wound motor are ordinarily connected across the line except during the starting period. The armature terminal voltage is thus approximately constant. The counter-voltage must be just enough less than the impressed voltage to permit the required load current to flow through the armature circuit resistance. Since the counter-voltage must be but a few volts less than that impressed upon the armature it follows that the counter-voltage of the motor must be nearly constant. Counter-voltage is pro-

portional to field flux and speed. Since the field flux is constant it follows that the speed will be maintained at nearly the same value, regardless of load. The shunt motor is essentially a constant speed machine. Increase of load requires corresponding increase of armature current to supply the necessary torque. To allow the added current to flow through the armature circuit resistance the counter-voltage must fall slightly. This decrease of counter-voltage is attained through a slight drop in speed. The speed of an ordinary shunt-wound motor falls off from 3 to 5 per cent from no-load to full-load. The speed regulation is then said to be 3 per cent or 5 per cent.

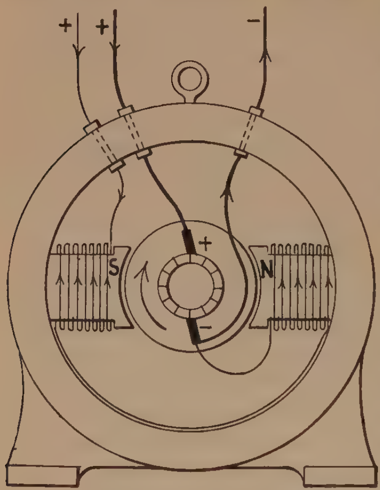

Fig. 7.—Connections of simple shunt motor.

Effect of Field Resistance.—The constancy of speed of a shunt motor is due to the steady field flux obtained by connection of the field coils across the line, securing a constant exciting current. The value of this exciting current depends upon the resistance of the shunt field coils. The resistance of these coils is about 20 per cent higher when they are hot than when they are cold, causing a corresponding change in exciting current. This does not bring about a 20 per cent change in speed because the iron of the fields is worked above the knee of the saturation curve. Here a 20 per cent decrease of field current will cause a decrease of 4 to 5 per cent in the field flux. In consequence of this weakening of the field, the speed rises a corresponding amount in order to maintain the required counter-voltage. The speed of an ordinary shunt motor is about 4 per cent higher hot than cold. In some cases a certain operating speed is found most effective for the driven machine. The effect of temperature rise may then be counteracted by use of a

rheostat in the shunt field circuit. When the motor is started cold resistance is inserted in series with the field. As the latter warm up the resistance is cut out to maintain the speed at the desired point.

Effect of Brush Position.—The brushes of any direct-current motor bear upon commutator bars to which are connected armature coils located approximately midway between main poles. It is possible to vary the speed of a simple shunt motor (without interpoles) to a limited extent by shifting the brushes. The speed change takes place because the brushes then span coils differently located under the main fields and thus giving different values of counter-voltage, and also because of the influence of armature reaction as will be later explained. Shifting the brushes against the rotation raises the speed. Shifting them with the rotation lowers the speed.

Shifting the brushes affects the commutation and the speed regulation and the movement permissible is limited to positions affording sparkless commutation at all loads. Shifting the brushes from the best commutating position is a dubious practice in any case and is not to be tolerated at all with interpole motors.

Torque Characteristic.—The torque of a motor depends upon the field flux, the number of armature conductors and the armature current. Since the field flux of a shunt motor is approximately constant, the torque increases in proportion to the armature current. Upon overloads the demagnetizing influence of the armature affects the main flux and causes the torque to rise more slowly. A shunt motor will exert a breakdown torque three to three and one-half times full-load value. Heavy overloads are accompanied with considerable drop in speed, rapid heating and severe sparking.

Starting Ability.—In starting any direct-current motor the flow of current during the accelerating period is restricted by insertion of external resistance in series with the armature to reduce the voltage at its terminals. By means of suitable resistance it is possible to restrict the current to any desired degree. Many motors are called upon to exert full-load torque or more during the starting interval. Torque is proportional to field flux and armature current. Since the field of a shunt

motor is of fixed strength it follows that in order to develop 150 per cent starting torque about 150 per cent full-load current must be permitted to flow. A shunt motor is able to exert a good starting torque but only at the expense of a large starting current.

Characteristics.—Figure 8 shows the characteristics of a typical shunt-wound motor. The constancy of speed is here evident. The torque curve is a straight line over the ordinary

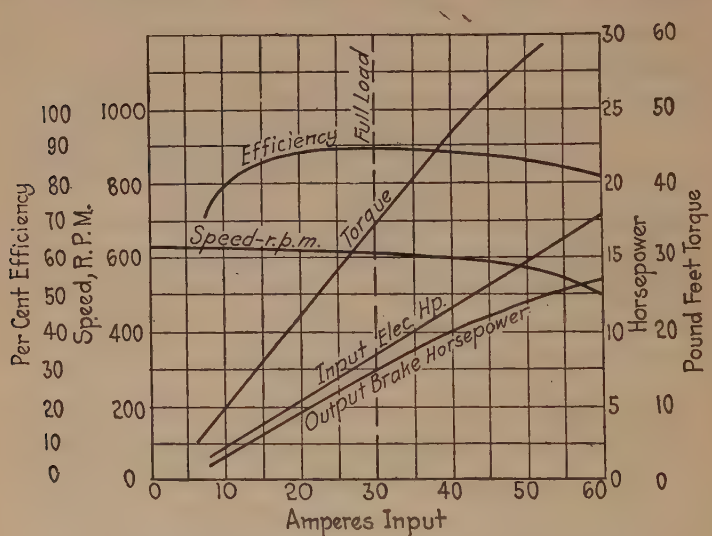

FIG. 8.—Characteristic curves of a typical shunt-wound motor.

working range. It should be noted that the efficiency remains high over a considerable load range, there being little change from 75 per cent load to 125 per cent load.

Applicability.—The shunt motor meets the requirements of a large range of industrial applications. The majority of individually driven machines operate at a single fixed speed. Practically all group and line-shaft drives fall in this class. The characteristics possessed by the shunt motor render it the best suited direct-current motor for the majority of constant speed drives.

SERIES-WOUND MOTORS

Principles of Action.—The series motor, as its name implies, has its field circuit connected in series with the armature as shown in Fig. 9. The field coils comprise a few turns of comparatively large wire since they carry the total load current, whereas in the shunt motor the field coils are made up of a large number of turns of small wire carrying a current perhaps one-fiftieth the value of the armature current. The characteristics of the series motor differ radically from those of the shunt motor. Since the field coils are connected in series with the armature, the field current varies with the load on the motor. As load is added greater current is required to produce the necessary torque. This current, flowing through the series coils, increases the field ampere-turns directly and, to a modified degree, increases the intensity of the main field magnetism. This makes possible the development of the required counter-voltage with slower rotation. Consequently the motor speed drops off. The series motor runs very slowly under heavy loads and the speed rises rapidly as the load is removed. If the motor be relieved of all load the current is so small that the field magnetism is almost *nil* and the armature must revolve at an enormous rate to maintain the counter-voltage. Therefore series motors are said to run away on no-load and they are seldom used with belted drive or elsewhere when it is possible for the load to be entirely removed. Because of the variation of speed with load, series motors are termed varying speed motors as contrasted with the constant-speed shunt type.

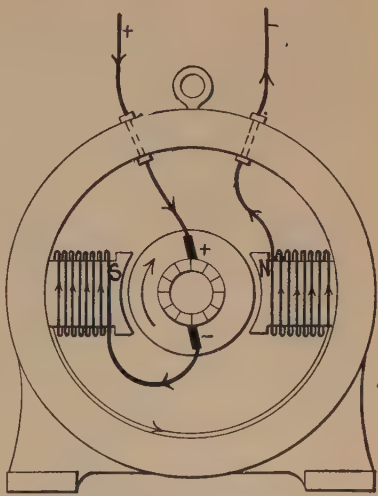

Fig. 9.—Connections of simple series motor.

The speed of a series motor varies because of the change in field strength accompanying load changes. Under light loads an increment of field current has greater influence than under heavy loads after the iron has become saturated. The speed of the series motor is thus more steady under heavy loads than under light loads. Figure 10 shows the characteristics of a series-

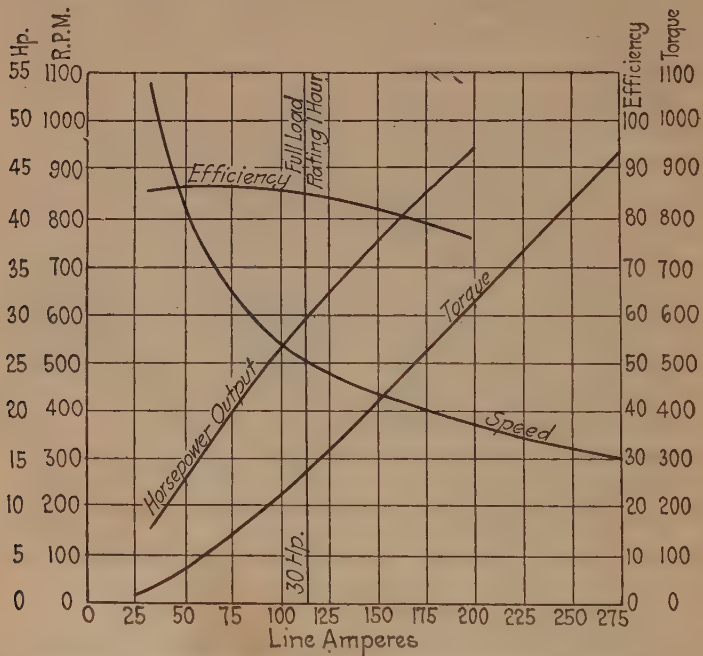

FIG. 10.—Characteristic curves of a typical series-wound motor.

wound motor. Temperature has little influence on the speed of a series motor. The nameplate rating of a series motor is its full-load speed.

Torque Characteristics.—Increase in current in a series motor increases the torque, directly due to increased armature current and also by strengthening the field magnetism. Therefore the torque of this motor is extremely high under heavy loads where the strong current works the iron well into saturation. The standstill torque of a series motor may be several times full-load torque. Heavy overloads may be handled

successfully by series motors without injurious sparking. Under heavy loads the fields are well saturated so that armature reaction has comparatively little influence. Moreover, in the operation of most series motors, periods of heavy load are alternated with periods of light load running. During the periods of light load the brushes erase from the commutator the effects of a little sparking due to overloads. Because of the heavy torque characteristic of the series motor at low speeds and at standstill this type is excellent in its starting and accelerating ability. It will start a much heavier load than a shunt motor and will accelerate with less current input and little or no sparking even with severe demands.

Efficiency.—The efficiency of series motors is usually somewhat lower than that of shunt motors of similar size. This is largely because of the lesser importance of efficiency due to the fact that these motors run comparatively little at their rated loads. They are continually accelerating and stopping. Greater saving is possible through proper application and control than through liberal design in the motors themselves. Because of the intermittent duty the material in series motors is worked harder than in shunt motors and advantage is taken of off-peak periods to radiate the higher losses.

Applicability.—The largest single application of series motors is for electric traction, this type of motor being used almost exclusively for traction service. For similar industrial work such as cranes and hoists the series motor is nearly always used if direct current is available. Here the variation of speed with load is particularly favorable. For instance, when lifting a heavy piece with a crane it is usually desirable to proceed slowly. When running light it should be possible to make considerable headway to cover ground rapidly. The enormous standstill torque of the series motor renders it well suited to hoisting and manipulating service and all work of this class where frequent acceleration under heavy load is demanded. Series motors are not widely used for continuous duty but find a few applications of this character. Small ventilating fans, for instance, are often direct-connected to series motors. Since the load increases rapidly with the speed, the series motor is held down to a fairly constant rate. In the smaller sizes such

motors may often be thrown directly upon the line with no starting device since the fan requires little torque at low speed and since the motor accelerates rapidly with comparatively small current intake.

COMPOUND-WOUND MOTORS

Principles of Action.—Compound-wound motors are a composite of the series and the shunt-wound types, there being two entirely separate sets of coils upon the field poles. One set, consisting of many turns of fine wire, is connected across the line as in a shunt motor. The other set, consisting of a few turns of coarse wire, is connected in series with the armature. If the shunt and series coils act in the same direction the motor is said to be cumulatively compound-wound, if they act in opposition, it is differentially compound-wound. Figure 11 shows the essential connections of a cumulatively compound-wound motor.

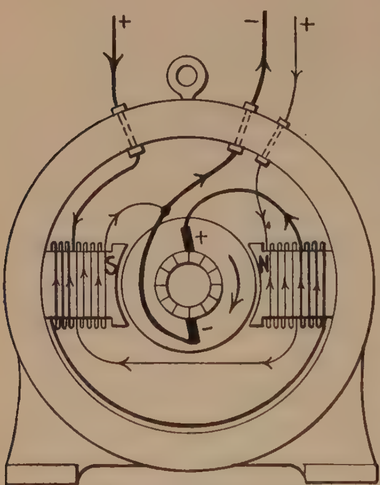

Fig. 11.—Connections of compound-wound motor.

The magnetizing effect of a coil is measured by the product of the current in amperes by the number of complete turns of wire. The shunt coil, having a small current flowing through a large number of turns, may have a magnetizing effect comparable with the series coil which has a heavy current flowing through a few turns. The ratio of series to shunt ampere-turns may be varied within any limits. Some motors are built with about 10 per cent shunt ampere-turns merely to prevent the motor from running too fast at light loads. Others are built with as low as 10 per cent series ampere-turns. Ordinarily

about 20 per cent of the ampere-turns at full load are in the series coils and motors are said to be 20 per cent compounded. Motors in which the series effect is desired to be more pronounced are frequently built with 40 per cent compounding. The series turns of a compound motor have little influence at light loads. In speaking of the ratio of ampere-turns full-load conditions are referred to.

Characteristics.—The characteristics of compound-wound motors combine in varying degrees the features of shunt and series motors. Cumulatively compound-wound motors, which

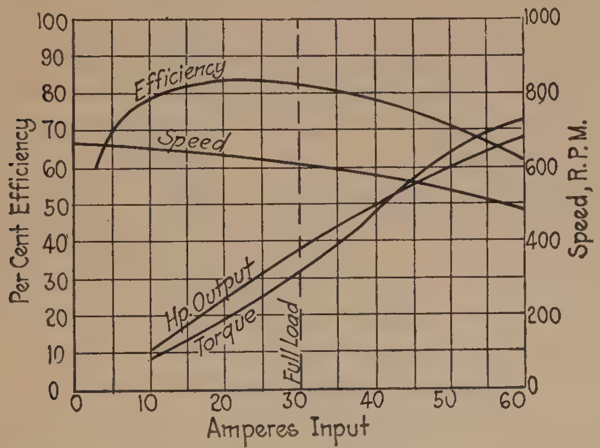

FIG. 12.—Characteristic curves of a compound-wound motor (20 per cent).

are the more common type, have speeds which decrease with an increase of load and torques which increase rapidly with addition of load. Figure 12 shows the characteristics of a typical 20 per cent compounded motor. The compound-wound motor shares with the series motor, to some extent, the ability to develop high torque per ampere in starting. It also has a heavier break-down torque than the straight shunt motor. It is essentially a fairly constant speed motor with excellent pulling power on heavy loads and good starting power.

In speaking of the degree of compounding of a motor it is more specific to define the extent of the speed rise from full-load to no-load rather than to state the per cent of series or

shunt ampere-turns. Thus a motor may be described as being compounded for 150 per cent no-load speed, meaning that the speed at no-load is 150 per cent of the speed at full-load. The basis for this preference arises from the fact that magnetic saturation is an important factor. If the shunt ampere-turns are sufficient to saturate the iron, a given per cent of series ampere-turns will have a less effect than if the iron were not saturated.

Differential Compounding.—In a differentially compound-wound motor the field intensity is weakened as the load increases, since the series coils are in opposition to the shunt coils. Thus the speed increases with addition of load. In some cases this gain in speed will increase the load and start a cumulative action until the series ampere-turns predominate over the shunt ampere-turns. The motor will then suddenly stop and reverse rotation. Due to its unstable and undesirable characteristics this type is little used.

Applicability.—Compound-wound motors are employed extensively for elevator service and for many similar applications where a heavy starting torque and fairly constant running speed are required. They also find many industrial applications for pumps, compressors, shears, presses, reciprocating tools and the like, where irregular loads with severe peaks are encountered together with a demand for fairly constant rotative speeds. They are also used where it is desired to protect the motor to some degree by its decrease in speed under heavy loads and for many other special purposes. The various uses for compound-wound motors are discussed in the companion volume, " Electric Drive Practice," Chapter II.

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Note.—In general, bibliography sequence is based on dates of publication and technical society proceedings are given precedence over magazine articles.

CHAPTER III

SPEED CONTROL OF DIRECT-CURRENT MOTORS

Inherent Speed Regulation.—We have seen that the ordinary shunt motor is primarily a constant speed machine, that the speed of the series motor varies over a wide range and that the compound-wound motor has a characteristic intermediate between these two. The speed fluctuations mentioned have been inherent in the machines themselves, occurring in consequence of load change. In each case a certain speed corresponds to a definite load. This automatic variation in the rate of rotation is termed speed regulation and motors whose speeds fluctuate widely in this manner are called varying speed motors.

External Speed Control.—It is possible to control the speed of a direct-current motor by external means. Change of rotation rate by modification of operating conditions is termed speed control. The speed of some direct-current motors can be varied gradually over a considerable range, remaining, for each setting, practically unaffected by the load. Such motors are called adjustable speed motors. The difference between varying speed and adjustable speed should be clearly understood. The terms are often confused by those who do not comprehend their exact meanings. Likewise, the distinction between speed regulation and speed control should be noted.

SPEED ADJUSTMENT BY FIELD-CONTROL METHODS

The Adjustable Speed Shunt Motor.—The adjustable speed direct-current motor is dependent for its performance upon the fact that the counter-voltage is proportional to speed and field flux. If the field current be changed the field magnetism is affected. This, in turn, requires a change in speed in order that the necessary counter-voltage be maintained. If an

adjustable resistor be connected in series with the shunt field of a shunt motor, or a compound-wound motor having a small degree of compounding, the speed may be adjusted to any desired point within limits and will remain approximately constant at that point regardless of load changes. Figure 13 shows the connections for an adjustable speed shunt motor. The machine is designed to operate at the lowest speed in its range as a simple shunt motor. As resistance is introduced into the shunt field circuit, the speed increases until a point is reached such that commutating conditions, instability of speed, or centrifugal stresses prohibit further increase. Motors

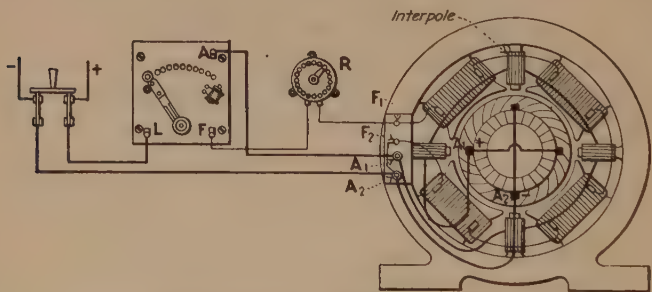

Fig. 13.—Connections of an adjustable speed motor.

are built commercially with speed ratios of two to one, three to one or four to one and they have been built for ratios as high as six to one. In other words, the maximum speed may be two, three or four times the minimum speed, the number of increments of speed depending upon the number of divisions of resistance in the controller.

Torque and Power Characteristics.—The horsepower output of a motor depends on two elements, torque and speed. Torque is proportional to field flux, number of armature conductors and amount of armature current. Speed depends upon the impressed voltage, the number of armature conductors in series and the field intensity. It is evident that if an increase in speed be brought about by decreasing the field intensity, the torque developed per armature ampere is reduced. The current capacity of a given armature is approximately constant, regardless of the speed. Thus, as the speed of an

adjustable speed motor is increased by field weakening, the torque capacity decreases as the speed increases. Since horsepower is proportional to the product of torque and speed, the decrease in torque capacity is offset by the increase in speed and the horsepower capacity remains approximately constant. At the lowest speed maximum field current flows and the iron is saturated. A higher torque is required to develop rated horsepower at the lower speed and approximately the same armature current is taken as at high speed. Since the materials are worked harder and the ventilation is poorer, the heating

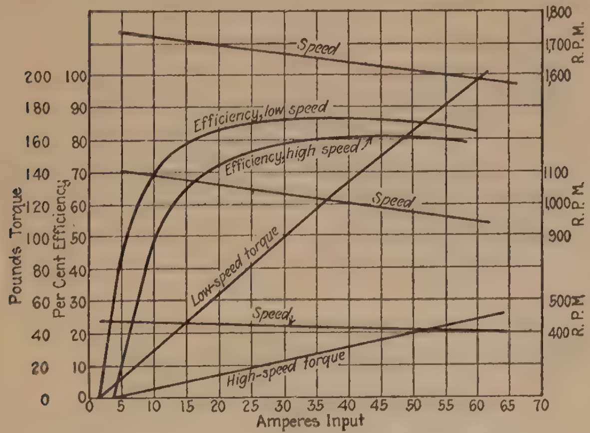

FIG. 14.—Characteristic curves of an adjustable speed motor with field control.

tendency is more pronounced. Temperature rise and torque limit the horsepower rating at low speed. Consequently the frame size is determined by the low speed rating and must correspond to that of a constant speed motor rated at the rotation corresponding to the minimum speed of the adjustable speed motor. A 5 hp., 400 to 1,600 r.p.m. adjustable speed motor for continuous service and a 5 hp., 400 r.p.m. constant speed motor are the same size. Motors designed for low speeds are larger and more costly than those delivering the same horsepower at higher speeds, due to the greater torque required per horsepower output. This being the case, a drive using an adjustable speed motor may have a higher

first cost than one using a constant high speed, low-cost motor with mechanical speed-changing devices. Figure 14 gives the characteristic curves of a typical adjustable speed shunt motor with field control.

Efficiency.—Since the field current of a shunt motor does not exceed 3 per cent of the total load current, the loss incident to insertion of resistance is small and this is a highly efficient method of speed control. As a rule the efficiency at low speed is slightly higher than at high speed. The iron loss and field copper losses are greater at low speeds but the losses due to windage and brush and bearing friction at high speeds more than offset the gain. Maximum efficiency usually occurs at an intermediate speed.

Applicability.—Adjustable speed shunt-wound motors are extensively used for individual drives where a selective range of speeds is desired together with good regulation at any point. High efficiency, easy and exact manipulation and steady running render the system generally the most satisfactory adjustable speed drive available. Motors of this type are used extensively for machine tool work where their characteristics fit the requirements to a nicety.

Field Control with the Series Motor.—The use of a rheostat in series with the field circuit is applicable only to the shunt field of a shunt or compound-wound motor. In a series motor it would be obviously useless to insert series resistance for the purpose of regulating the field strength. Speed adjustment by field control is not common practice with series motors. It does find a few applications however. The field may be adjusted either by shunting a part of the load current around it or by short circuiting a part of the field turns. Either arrangement serves to weaken the field and thus increase the speed even with the load constant. Inasmuch as the resistance of a series field is comparatively low, the shunting or short-circuiting resistance must be very low indeed and any wiring in this circuit must be heavy in order that its resistance may not greatly modify conditions.

Compound-wound motors are occasionally but not commonly arranged for adjustable speed duty with shunt field control.

SPEED ADJUSTMENT BY ARMATURE RESISTANCE CONTROL

The speed of a direct-current motor may be decreased by lowering the voltage impressed upon the armature. This is because of the fact that, when the impressed voltage is reduced, the counter-voltage necessary is also reduced to a like degree. Figure 15 shows a shunt motor with an adjustable resistor connected in series with the armature circuit. The load current flows through this resistor, causing a voltage drop. The voltage at the armature terminals equals line voltage minus the drop in the resistor. This drop depends upon the amount

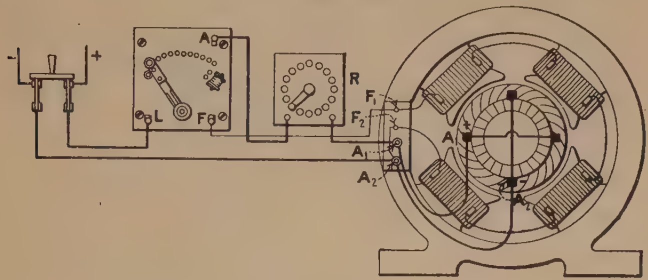

FIG. 15.—Connections of a shunt motor with resistance in series with armature.

of resistance and the amount of current. By changing the resistance in the controller the speed of the motor may be adjusted. With a given resistance the drop depends upon the current which, in turn, depends upon the load. An increase in load causes a rise in current. This, in turn, increases the voltage drop and subtracts a greater voltage from the line. For a given resistance value the armature terminal voltage depends upon the load. Since the speed depends upon the voltage at the armature terminals, the speed varies with the load. Figure 16 gives characteristic curves of a shunt motor with armature control, the speed regulation being shown for several settings of the controller. Inasmuch as the armature current at no-load is small, there is little drop, even with comparatively high resistance. Consequently, under light loads the speed is nearly the same as if there were no resistance in the circuit. This method affords little speed adjustment for light

load conditions. The heavier the load the greater the speed range available. It should be noted that the speed range obtained by armature resistance control lies entirely below the rated full field speed of the motor whereas, with field control, the speed range lies above this point. Sometimes the two methods are employed to obtain a range greater than that afforded by either method singly. This is particularly feasible if the load at reduced speed is relatively light or if slow speed operation is only occasional or intermittent.

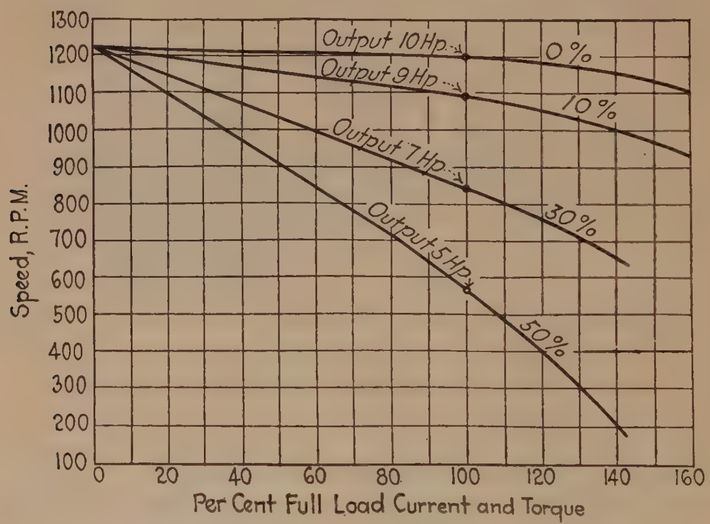

FIG. 16.—Speed characteristics of a shunt motor with armature resistance control.

Selection of Resistors.—Since the degree of speed variation secured by armature resistance depends upon the load, it is highly necessary that exact working conditions be known if correct speed values are to be obtained. Consider, as an example, the 10 hp., 1,200 r.p.m. motor shown in Fig. 16. It is intended to reduce this speed to 600 r.p.m. A controller is supplied such that, with all resistance cut in, the speed will be 600 r.p.m. with full load torque. After installation it is found that the driven machine requires but 80 per cent of full load torque. The current corresponding to 80 per cent torque is

insufficient to bring the speed down to 600 r.p.m. The minimum speed of the motor is seen to be 710 r.p.m., as indicated at 80 per cent torque on the curve representing maximum resistance setting of the controller. The desired minimum speed, 600 r.p.m., cannot be attained with this load without additional resistance.

A successful armature control application requires a definite preliminary knowledge of the exact load and its behavior with respect to the speed. These data must be furnished the controller manufacturer to enable him to fit requirements rightly. Insufficient and inexact data are a not infrequent cause of unsatisfactory performance of armature control installations. Questions relating to the proper determination of series resistors for speed regulating duty are considered in Chap. XI.

Efficiency.—Since the entire load current of the motor passes through the resistors of an armature control speed regulator the loss therein may be considerable. Since the field strength remains constant, the armature current at any speed depends upon the torque demanded at that speed. With a constant torque load the armature current is the same for all speeds, therefore the resistance loss increases directly as the speed is reduced. At half speed one-half of the electrical input is wasted in resistance, the other half being input into the motor. The over-all efficiency is thus below 50 per cent. If the torque demand decreases with reduction in speed, both the output and the input are correspondingly reduced. The efficiency is still approximately proportionate to the speed. In such a case, however, the actual losses do not increase in proportion to the speed reduction, due to the decreased torque and consequently decreased current. In any case the losses are less serious as full rated speed is approached. The allowable speed reduction is limited both by poor speed regulation and resistance losses. About 25 per cent reduction is quite satisfactory for continuously running, steadily loaded drives. Reductions as great as 50 per cent are sometimes used. Reductions of 50 to 90 per cent are used for intermittent operation or for manipulating duty under the attention of an operator. It should be noted that, due to the high resistance losses, suitable speed regulators are required which are capable of dissipating

the energy lost in the resistors. Ordinary starters are not intended for this service.

Applicability.—Armature control is suited for highly intermittent duty, for manual regulation and for continuous drives requiring constant torque or decreased torque at decreased speeds. Because of poor efficiency and fluctuating speed tendencies the applications are limited. It is not at all suited for machine tool drives where changing loads are involved and exact, constant speeds are desired. It is used extensively for traction service, cranes and hoists, operations where the speed is continually under manual control. It is used for printing presses and elsewhere for slow speed "setting up" work, where the motor normally operates at higher speeds. It is applied quite regularly for blowers and fans, where the load is steady and the maximum motor capacity is required at high speed but where, at low speeds, the losses are greatly reduced because of the lesser loads.

SPEED CONTROL BY ARMATURE SHIFTING

The Armature Shifting Motor.—The methods of securing adjustable speed thus far considered have involved changes of an electrical nature by means of controllers and inserted resistors. It is possible to obtain speed adjustment entirely by mechanical means. We will describe the method employed in the most commonly used motor of this type shown in Fig. 17. In this motor speed adjustment is obtained by gradually shifting the armature endwise, along its axis, away from its normal position under the main field poles. The machine is so constructed that shifting the armature does not alter the position of the main shaft or pulley. When the armature is in its normal position the motor operates at minimum speed. As the armature is shifted out from under the main poles the effective area of the poles is reduced and the magnetic flux cut by the armature conductors proportionately decreases. The air gap is also increased by axial movement of the armature because the armature core is slightly tapered in the form of a truncated cone and the bore of the fields is similarly tapered. Increase in speed thus becomes necessary in order to maintain

the counter-voltage. The further the armature is shifted from under the main poles the faster it revolves. With the armature in a given position it behaves practically as a constant speed motor and maintains steady rotation under varying load. Motors of this type are thus truly adjustable speed motors and have the same general characteristics as motors employing the field resistance method of speed control. As the armature is shifted the effective flux is reduced and the torque consequently decreased. The speed, however, increases.

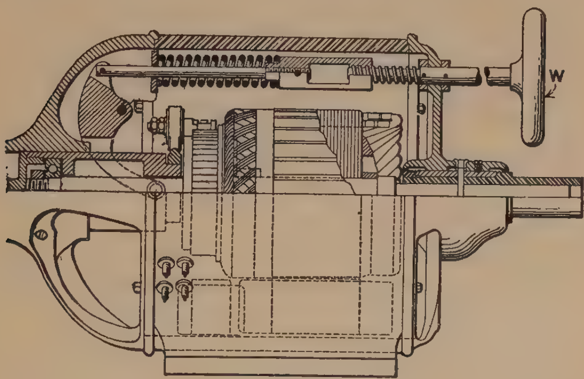

FIG. 17.—Section through motor in which adjustable speed is obtained by shifting the armature.

Since horsepower is proportional to torque and speed, it is evident that this motor is essentially a constant horsepower machine. It should be noted, however, that the starting torque available depends upon the position of the armature. When starting heavy loads the armature should be located well within the fields. This motor thus has a weak point as applied for frequent starting under full-load, high-speed conditions. Also, due to the magnetic pull of the field upon the armature, the latter has no end play except when located directly under the main poles.

Characteristics.—Commutation is quite satisfactory in motors of this type. The fields are always saturated for the reason that the cross-section of the iron carrying the flux decreases as the armature is shifted laterally. Also the ratio

of armature to field ampere-turns is constant. As a result there is little more distortion under high-speed conditions than under normal low-speed conditions. In addition, interpoles are provided in the commercial motors of this type to provide good commutating conditions. The characteristics of a machine of this design are shown in Fig. 18.

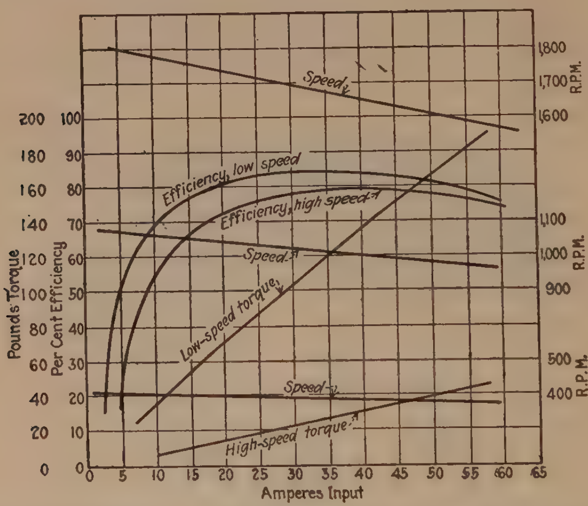

FIG. 18.—Characteristic curves of a shunt motor with armature shifting control.

Adaptability.—A few advantages are realized by this type of motor. The speed changes are obtained by turning a hand wheel attached to the motor frame and there are available an unlimited number of intermediate speeds. With field control the speed increases in steps, corresponding to the points of the controller. The greatest advantage of this type of motor is in the wide range of speeds available. With field control a range of 4 to 1 is usually a maximum. The armature-shifting method makes possible a range of speed as high as 10 to 1. This motor is therefore an excellent one to use where very wide range of speed is desired. It finds quite extensive use on a variety of machine tools.

MULTIPLE AND VARIABLE-VOLTAGE SYSTEMS OF SPEED CONTROL

Multiple-Voltage System.—It has been stated previously that the speed of a direct-current motor may be varied by changing the voltage impressed upon its armature and it was shown how this may be accomplished by the insertion of series resistors. Other methods may be employed to obtain speed control by variation of applied voltage. The so-called "multi-voltage" system is sometimes adopted. Most commonly this is arranged to provide 115/230 volts from a three-wire distribution system served by three-wire generators, rotary converters, balancer sets or series generators. The field circuit of the motor is connected permanently to one voltage but the armature may be connected across either voltage, series resistors being used during acceleration and transition periods, as usual. When operating at half voltage, approximately half speed results. As the field strength is unchanged, the torque per ampere of armature current is not affected by the voltage used. A motor used on a multi-voltage system thus has inherently a fixed torque capacity and can deliver a higher horsepower rating on the high than on the low voltage. The speed-torque characteristic on both voltages is similar and is determined by the motor. Thus a shunt motor will have a flat speed characteristic on either 115 or 230 volts, the speed on the lower voltage being about half that on the higher. The motor is a normal 230-volt design and has no special features. This general method of speed control is well suited in some cases where the load demand is of a constant torque character as a smaller motor frame may be employed than would be required for single voltage operation with field control. This is because the higher speed associated with the greater horsepower is obtained with strong rather than weakened field and the torque per ampere is therefore greater.

Primarily in order to minimize resistance losses, a system of multi-voltage control has been adopted for elevator service, in which four voltages, respectively 25, 50, 75 and 100 per cent normal, are used. Figure 19 is a diagram showing the general arrangement of such a system. A balancer set that is

capable of producing four different voltages is connected across the line. The field winding of the elevator motor is also connected across full voltage. When starting, the motor armature is first connected to points A and B. After it has accelerated to a certain speed, it is disconnected from B and connected to C, thus connecting it to half voltage. Further acceleration is obtained by disconnecting from C and connecting to D, to obtain three-quarters of full voltage, and full voltage is ob-

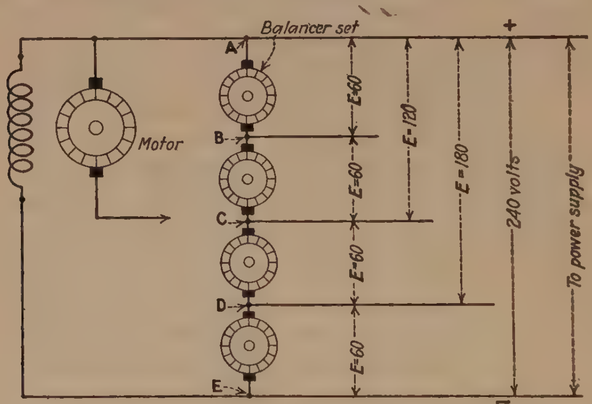

FIG. 19.—Schematic diagram of multi-voltage control system.

tained by disconnecting from D and connecting to E, where normal speed is obtained. A controller for accomplishing these transitions smoothly and without interruption of torque, is described in Chap. XV, page 357.

Ward-Leonard System.—Where the importance of the drive warrants the use of an individual generator to supply power to one motor, the speed of the motor may be controlled by varying the generator voltage, which is also the impressed motor voltage. The fields of both the generator and the motor must be excited from a separate source of constant potential. The armatures of the generator and the motor are connected together as indicated in Fig. 20. No armature circuit resistance is necessary as the motor can be started by building up the generator voltage from zero to any desired point by adjustment of the generator field strength. A wide speed range is afforded, ranging from a creeping speed to rated speed of the

motor with maximum voltage. For any given generator voltage the speed of the motor, which is usually shunt-wound,

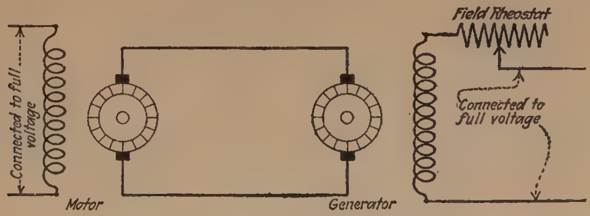

FIG. 20.—Connections for variable voltage (Ward–Leonard) system of motor speed control.

remains quite constant, regardless of load. As the motor field is of constant strength, the torque per armature ampere is

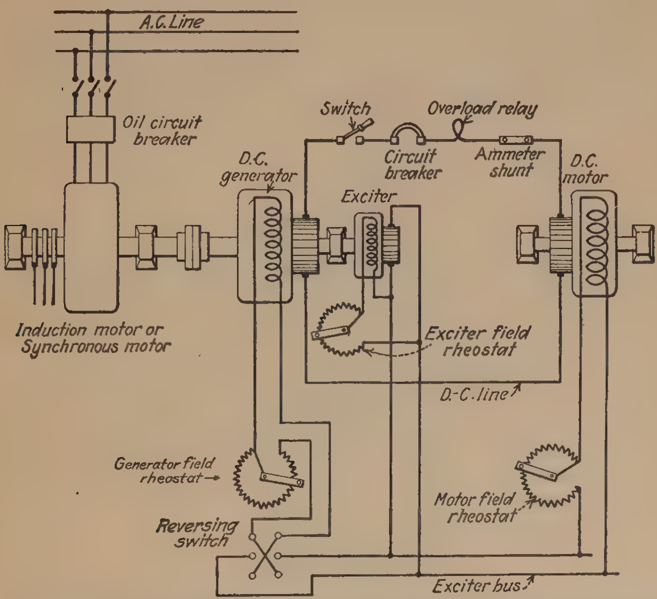

FIG. 21.—Simplified diagram of connections of a variable voltage (Ward–Leonard) drive.

fairly definite and the drive has a constant torque rating. Lack of ventilation at very low speeds may reduce the capacity. This variable voltage method of speed control is commonly

known as the Ward-Leonard System. Figure 21 shows the general arrangement of machines and the scheme of connections for an industrial application of this system.

It may be noted that, by reversing the fields of the generator, the polarity of the generated voltage may be reversed. This results in reversed rotation of the motor. The fact that both the direction of rotation and the speed may be controlled by manipulation of field circuits alone, involving low currents and low resistance losses, is of distinct value in the case of some very large motors where switching of heavy armature currents would be difficult and armature resistance losses would be excessive were ordinary methods used.

Combination Methods.—Not infrequently two or more methods of speed control are combined either to obtain a wider range or to meet the drive requirements most effectively or with minimum cost. Armature control and field control are quite frequently combined to provide a wider speed range, to obtain slow speeds for machine adjustment or to minimize motor cost. Multi-voltage control may be combined with either armature or field control or both, to give a wide and uniform speed range. Field control is frequently provided on motors used with the Ward-Leonard, variable-voltage system. With this arrangement a wide range can be obtained at minimum generator cost and with better speed regulation characteristics than may be obtainable with voltage control alone. It should be noted that, where a speed range is divided between two control systems, the characteristics of each method prevail over its portion of the range. Thus where any method of armature voltage control is employed, a constant torque rating is obtained. Where motor field control is employed, a constant horsepower rating is afforded.

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See also Bibliography of Chaps. II, p. 16 and IV, pp. 43–44.

CHAPTER IV

ARMATURE REACTION AND OTHER FACTORS

ARMATURE REACTION

Definition.—A number of factors enter to complicate the simple principles of motor action which have been previously discussed. Among the foremost of these is armature reaction. This is a general term used to designate the several effects of the magnetizing influence of the current flowing in the armature coils.

Effects of Armature Reaction.—Figure 22 illustrates the armature and field poles of a two-pole motor. It may be seen

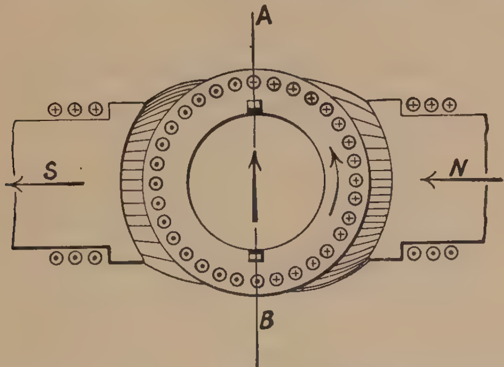

FIG. 22.—Armature reaction in simple motor with brushes in no-load neutral position.

that, just as the field coils produce a flux in a horizontal direction, so the armature coils, carrying current, tend to produce a cross-field as indicated by the arrow. This cross-field has the effect of increasing the flux flowing *into* the lower half of the armature and increasing the flux flowing *from* the upper

half. As a result of the combined field and armature magnetizing forces the flux is distorted in the general manner indicated. As the armature magnetizing force is largely proportional to the armature current, the distortion is small at no load and increases with the load. The extent of the distortion depends upon the ratio of armature ampere-turns to field ampere-turns and upon the air gap. A motor with a wide air gap has magnetic circuits of high reluctance and requires a strong field magnetizing force, and its flux distribution is less disturbed by a given number of armature ampere-turns. The shape of the air gap and pole tips also plays a part, due primarily to the effects of saturation in restricting field distortion.

Brush Position.—The direction of current flow must be reversed at the instant that each armature coil is short-circuited by the brushes. Due to the fact that the current is changing value, a self-induced voltage is set up in the short-circuited coil, tending to prevent this change. In order to overcome this influence and to bring about complete reversal of current before the coil ends pass out from under the brushes, some voltage must be generated in the short-circuited coil in a direction to assist the reversal of current. In a motor not equipped with interpoles this voltage is obtained by shifting the brushes in a direction against the rotation, bringing the shorted coil into a zone of light flux of proper direction to generate the voltage desired. The proper amount of brush shift depends upon the flux distribution. As the flux distribution under load differs from that at no load, the correct brush position for one condition will not be entirely correct for another condition. The degree of error depends upon the degree of flux distortion and is therefore greatest in those motors whose design permits strong distortion of the field flux.

In an adjustable speed motor the field is relatively weak at high speeds and the armature magnetizing influence relatively more effective in producing flux distortion. For this reason it is particularly difficult or impossible to locate a brush position which will afford good commutation over a range of loads.

It should be noted that when the brushes are shifted as shown in Fig. 23, the axis of the armature magnetization is

along the line *B-A*. This may be reduced to two component fields, namely a cross-field causing distortion and a component which opposes the main field magnetization and thus exerts a demagnetizing influence. The latter affects the speed regulation of the motor, tending to give it a rising speed characteristic. Incidentally it may be mentioned that, if a motor having a considerable brush shift be operated with field circuit open, it will tend to revolve due to the field set up

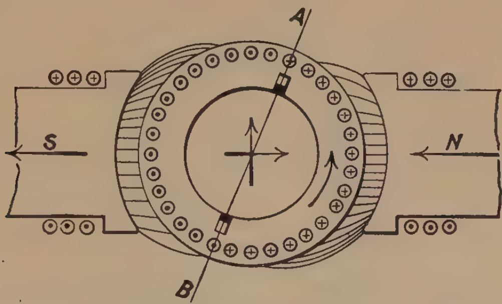

FIG. 23.—Armature reaction in simple motor with brushes shifted from no-load neutral position.

by the armature ampere-turns. The direction of rotation is in reverse to normal.

THE INTERPOLE

Functions of the Interpole.—The purpose of shifting brushes has been mentioned, namely, to place the commuted coils in a flux which will generate in them a small voltage to assist the reversal of current flow. This method is not very satisfactory since the flux in which the commuted coils are located is decreased by field distortion as the load comes on. It is also decreased when the field is weakened to increase the speed. To create proper commutating conditions this flux should increase in proportion to the armature current, since the voltage of self-induction in the short-circuited coils varies in this proportion. It should also be the same at all speeds. The voltage of self-induction increases with the speed (frequency) and the commutating voltage should do likewise. This purpose

can be better accomplished if the brushes be fixed in their central position and interpoles be added midway between main poles as shown in Fig. 24. The interpole performs two functions, namely, it neutralizes the magnetizing influence of the armature and thus prevents the existence of the cross-field in the zone of the commuted coils; it creates a field in this zone to cause sufficient voltage to be generated in the commuted coils to overcome the effects of self-induction and to assist in

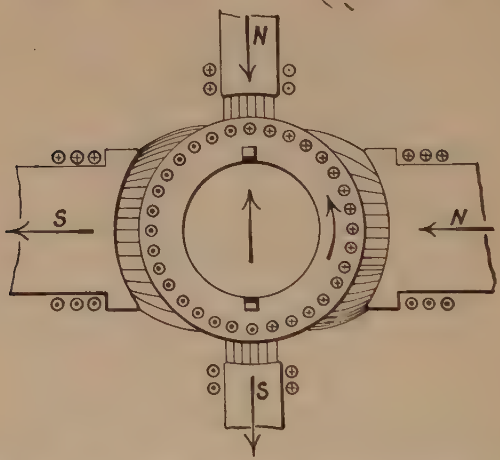

FIG. 24.—Magnetizing forces in motor with interpoles.

reversal of current flow. Both of these functions demand that the interpole strength vary in direct proportion to the load current. This condition can be approximated by connecting the interpole winding in series with the armature. Even with this arrangement the interpole strength is not always correct, due to the effects of interpole saturation and magnetic leakage between the interpoles and main poles. However, the commutation is greatly improved and, even with greatly weakened main field and high speed, good operation is obtained. Interpoles are now used in the great majority of direct-current motors. They are particularly beneficial in high-speed motors, in adjustable speed motors and in motors subject to wide fluctuation of load. They are also essential for most reversing motors, where brush shifting would be impossible.

Interpole Field Strength.—The armature cross-field is directly opposed to the interpole field. This makes it necessary that the interpole fields have sufficient ampere-turns to counteract this influence, with sufficient additional effect to set up the desired commutating flux.

Interpole Polarity.—The polarity of the interpoles depends upon the polarity of the armature. The interpoles in a motor should have the same polarity as the main poles preceding them against the direction of rotation as indicated in Fig. 24. If the direction of rotation be reversed by reversing the armature, the interpole fields must also be reversed. It is therefore proper to treat the armature-interpole circuit as a unit and not reverse one without the other. Particular care must be exercised if the brush yoke is shifted to adapt the motor for side wall or ceiling mounting, lest the armature be thus reversed without also reversing the interpole.

Number of Interpoles.—Some motors are provided with only half as many interpoles as main poles. This arrangement gives entirely satisfactory results but the interpoles must be of such strength as to set up a heavier commuting flux as only one side of each commuted coil is under an interpole. When the number of interpoles is half the number of main poles, the interpoles are all of the same polarity.

Brush Position.—It is essential that the brushes of an interpole motor be located accurately in a central position. If the brushes are given backward lead (against the rotation) a rising speed characteristic results which causes instability and sparking. If the brushes have forward lead, the commutating conditions are poor and a drooping speed characteristic obtains.

COMPENSATION

Purpose.—The influence of the interpole is restricted to a narrow zone under its pole tip. Aside from this it does not counteract or correct field distortion. In any direct-current machine the sum of the individual voltages between commutator segments over a brush span equals the full armature voltage. But the voltage between any two adjacent segments depends upon the strength of the field in which lie the

coils connected to these segments. Field distortion is principally detrimental in that it causes a peaked voltage distribution in the armature coils which results in a non-uniform distribution between brush studs of voltages between adjacent commutator segments. A non-uniform voltage distribution involves high voltages between some adjacent segments. The maximum voltage between segments must be restricted to prevent a tendency to flashing. Field distortion is particularly pronounced in adjustable-speed motors. At high speeds

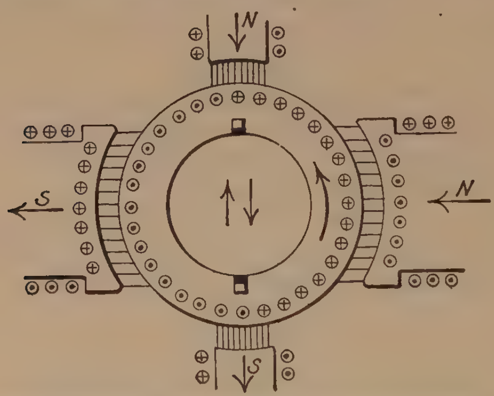

FIG. 25.—Magnetizing forces in motor with interpoles and compensating windings.

the armature reaction is especially effective in crowding the flux into the leading pole tips so that this part of the pole carries nearly as much flux when operating with weakened field as when operating with full field. The armature conductors, rotating at increased speed in the strong flux under the leading pole tips, have much higher voltages generated in them than when rotating at slower speed in an only slightly stronger flux. Thus the voltage between the commutator segments to which these conductors are connected, is much greater at high than at low speeds, the voltage distribution across the commutator is less uniform and the tendency to flashing more pronounced. It is possible practically to counteract the cross-field which causes flux distortion by introducing into the main field poles a distributed winding as indicated in Fig. 25. The magnetizing

effect of this winding directly opposes the cross-magnetizing influence of the armature. The distributed winding is connected in series with the armature so that its strength is proportioned to counteract the armature magnetization at all loads. A pole-face winding such as above described is termed a compensating winding. It operates to prevent flashing by giving a more uniform field distribution, decreasing the maximum voltage between adjacent commutator bars.

When compensating windings and interpoles are both used,

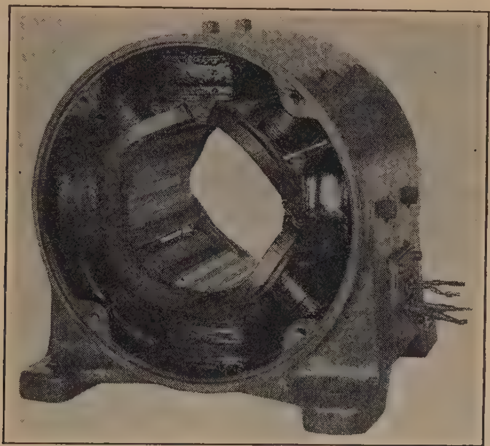

Fig. 26.—Field frame of a motor equipped with interpoles and compensating windings.

the strength of the latter is decreased as the function of the interpoles is partially served by the compensating windings. This has a direct influence on the ability of the motor to commutate overloads as it decreases greatly the interpole leakage flux and interpole saturation. Figure 26 shows the field frame of an adjustable speed motor in which a compensating winding is provided.

Compensating windings are undesirable from a practical viewpoint as they crowd the field coil space, obstruct ventilation and render repairs to field coils difficult. Therefore their use should be confined to applications where the benefit warrants the complication involved.

SPEED REGULATION

Factors Influencing Speed Regulation.—The speed of a direct-current motor is determined by the net armature voltage and the field flux. These values are subject to change with load, even in a shunt motor, thus affecting the speed regulation. As the load increases, the resistance drop in the armature increases; this in turn decreases the counter-voltage necessary and thus tends to cause a drop in speed. On the other hand,

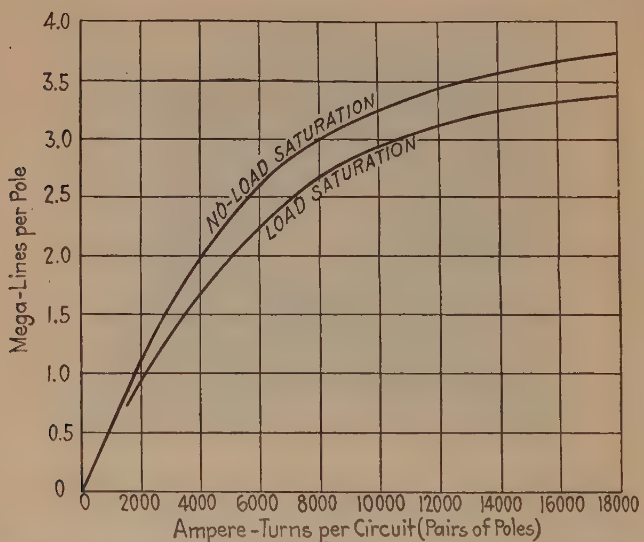

Fig. 27.—No-load and full-load magnetization curves of a motor.

due to field distortion, the flux is crowded into portions of the field poles, saturating them and thus increasing the reluctance. This results in a decrease in flux. The no-load and full-load saturation curves of a motor differ slightly, as shown in Fig. 27, due to the effect of saturation. The result of this flux decrease under load is to encourage a rising speed characteristic.

If the brushes of a simple shunt motor be given a backward lead, the demagnetizing influence previously mentioned under the general heading "Armature Reaction" tends to cause a rising characteristic.

The coils short-circuited by the brushes are so located that any current flowing in them has a magnetizing influence in line with that of the field poles. Any short-circuit current therefore tends either to strengthen or oppose the main field, depending upon the direction of current flow. This in turn depends upon the commutating conditions. If an interpole motor have sufficient commutating flux under the interpoles to cause a quick reversal of current, a demagnetizing action on the main field flux is probable, resulting in a tendency for the speed to rise under load. Thus, an over-strong interpole leads to instability.

The actual speed regulation curve of a shunt motor depends upon the relative prominence of the various factors above mentioned. If the resistance drop predominates, a drooping characteristic results. If demagnetizing influences more than offset the resistance drop, a rising speed tendency prevails. Usually the resistance drop prevails at light loads but at heavy loads the effects of saturation and demagnetization are more pronounced. Slow-speed motors usually have greater resistance drop than high-speed motors, and therefore tend to a more drooping characteristic.

The regulation of an adjustable speed motor is not necessarily the same at all speeds. Many factors enter. At high speeds, with weakened field, armature reaction is more effective in distorting the flux distribution and the consequent effect of saturation under load is more pronounced. Thus the regulation tends to be poorer at high speed than at low speed. Moreover, the regulation curve is usually more concave at high speed, departing materially from a straight line.

The interpole flux for a given current tends to be greater at high speeds since the main yoke of the motor is less saturated. On the other hand there is greater leakage between the main poles and interpoles, tending to saturate the latter more quickly. It is seldom possible to adjust the interpole strength correctly for all speeds, so it is adjusted for high speed and is usually a little under strength at low speeds.

Regulation Curves.—Figures 28, 29 and 30 show three speed regulation curves. Figure 28 shows a slightly drooping characteristic, usually most desirable. Figure 29 is the heavily

drooping characteristic of a slow-speed motor. The curve in Fig. 30 is caused by the resistance drop predominating at the lighter loads and field weakening at the heavier loads. Motors

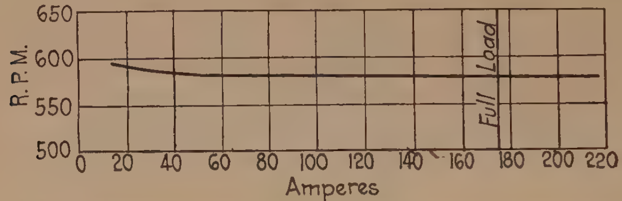

FIG. 28.—Speed regulation of shunt motor with flat characteristic.

having a rising speed characteristic are liable to be unstable. It is a practice of some manufacturers to equip such motors

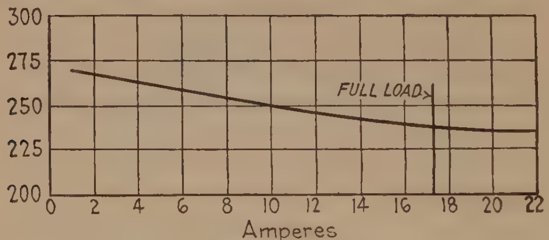

FIG. 29.—Speed regulation of shunt motor with drooping characteristic.

with a light compound winding on the main poles, just sufficient to counteract the rising speed tendency. In general, motors

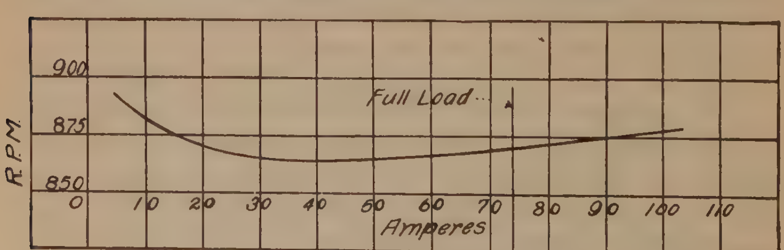

FIG. 30.—Speed regulation of a shunt motor with rising characteristic.

equipped with interpoles have closer speed regulation than similar motors not so equipped.

In compensated motors, armature reaction is practically

neutralized and the influence of flux distortion on speed regulation is thus prevented. Due to lesser magnetic leakage the effects of interpole saturation are also avoided. Compensated motors may be designed to give very close speed regulation at all speeds and the departure from a straight-line regulation curve may be made very small. This type of motor is therefore particularly suitable where extreme accuracy of speed regulation is desired.

EFFECT OF VOLTAGE VARIATION

Effect on Speed.—The speed of a direct-current motor will vary in some degree with the voltage impressed. The character of the load will then determine the corresponding extent of change in load which, in turn, will influence the amount of speed change. The torque may be independent of the speed, it may vary directly or inversely with the speed or it may vary in some other proportion.

Shunt Motor.—An increase in impressed voltage affects both the armature and the field circuit. The net result of a change in voltage is that derived from the combination of the two separate effects. If the field strength were to remain constant, the speed would vary in direct proportion to the voltage impressed on the armature. A change in voltage impressed on the fields causes a corresponding change in ampere-turns of field excitation. The effect on the flux depends upon the degree of saturation of the magnetic circuit. In a motor having a saturated magnetic circuit, a change in excitation has a relatively small influence on the flux. If the iron is worked well below saturation, as in an adjustable speed motor with weakened field, increase in voltage and exciting current causes a nearly proportional increase in flux. Thus, in a motor operating with saturated magnetic circuit, a change in voltage will cause a nearly proportional change in speed; in a motor operated with weakened fields, a change in voltage causes relatively little speed change. In the ordinary case a 10 per cent change in voltage will cause about 5 to 8 per cent change in speed.

Series Motor.—A change in voltage impressed upon a series motor will cause a proportionate change in speed if the load

current flow be constant. The extent of departure from this effect depends on the amount of load and its characteristic. If the load have a constant torque requirement a given current is necessary in the armature and field circuits to develop this torque, the field strength, determined by this torque and current, will be fixed, and the speed will vary in direct proportion to the voltage applied. If the load varies with the speed in some other manner, the field strength will be affected by the change in current incident to a change in voltage and the speed will be affected accordingly. If the torque demand increases with the speed, an increase in voltage, causing an increase in speed, will increase the load current, increase the field strength and thus limit the speed increase. If the motor is heavily loaded, so that the magnetic circuit is more or less saturated, the field flux is affected to a lesser extent by a change in load current. In general, in a series motor, a change in impressed voltage will cause a proportionate change in speed or a somewhat lesser change, as influenced by the load characteristic.

Sometimes two series motors are connected in series for half-speed operation and in parallel for full-speed operation. In an emergency, a single motor may be called upon to handle the entire load, operating on full voltage. In such a case, the effect of increased load is particularly marked and the single motor will attain only about 70 per cent (exact value differs in each case) of the full speed corresponding to parallel operation with two motors.

Compound Motor.—The compound motor without load is, in effect, a shunt motor and functions accordingly. Under load it partakes of the characteristics of the shunt or series motor, depending upon the degree of compounding. Most compound-wound motors are of the single-speed type and the fields are fairly well saturated under load. A decrease in voltage reduces the shunt ampere-turns and the field flux. If the load has a constant torque characteristic, an increased current is necessary to maintain the torque; this causes an increase in series ampere-turns which tends to maintain the flux. Thus the tendency is for the field flux to remain fairly constant. In general, the speed of a compound-wound motor varies considerably less than in direct proportion to the voltage.

A change in voltage on a compound-wound motor affects the degree of compounding and the regulation curve materially. An increase in shunt ampere-turns, due to increased voltage, decreases the influence of the series field ampere-turns, both directly and indirectly due to saturation. Thus an increase in voltage decreases the degree of compounding and vice versa.

Effect of Voltage Fluctuation.—Sudden changes of voltage have an important influence on the operation of motors, particularly when connected to loads of high inertia. Since a change in voltage ordinarily causes a change in speed, it follows that, in case of a sudden rise in voltage, the motor is called upon to accelerate the machine and overcome its inertia. The effect is similar to the rapid cutting out of the starting resistor on a motor driving a load of high inertia. For any given terminal voltage a motor has a definite speed regulation curve. When the voltage is changed, the motor is transferred from one regulation curve to another. If the motor have a flat speed characteristic the change from one operating curve to another is accompanied by a decided momentary inrush or drop in current. If the motor have a drooping speed characteristic, the effect is less pronounced. In some cases the current inrush incident to a sudden rise in voltage on a motor with flat regulation is sufficient to seriously overload the motor or trip protective devices. The hammer blow effect on the driven machinery and gearing is also undesirable. A sudden drop in voltage and current may cause the machine to overhaul the motor, giving back-lash in the gearing (also causing series lockout contactors to open; see Chap. XIV). For these reasons, a compound-wound motor is often to be preferred to a shunt motor for operation on circuits subject to voltage fluctuation. In any case voltage fluctuation affects both motors and machinery adversely.

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CHAPTER V

THE POLYPHASE INDUCTION MOTOR

The induction motor, as usually built, consists primarily of two parts, one stationary, the other rotating, each of which carries windings. In the ordinary design, the bore of the stator is slotted and carries distributed windings which are made up of coils often similar to those used in the armature of a direct-current motor. The rotor is also slotted and carries windings. That part of the motor carrying the windings connected to the power supply circuit is called the primary. The primary is usually the stationary outer part or stator. The revolving part, the rotor, is then the secondary.

Principles of Action.—The polyphase induction motor is the polyphase equivalent of the separately excited direct-current shunt motor. The action of the polyphase induction motor is easily and conveniently explained by the revolving field theory, which is justly popular. An explanation of this theory of action is given on following pages. This explanation, however, fails to bring out the important resemblance to the direct-current shunt motor above mentioned. We will therefore proceed first to establish this resemblance.

Figures 31*a* and 31*b* show the primary form of a two-pole two-phase induction motor. In theory and performance it duplicates closely the familiar squirrel-cage motor. In the squirrel-cage the rotor currents are free to distribute themselves along a plurality of paths which revolve with the rotor. In the commutator equivalent, the paths for the rotor currents are fixed in space by means of brushes which are independent of rotor movement. The current distribution in the rotor conductors is similar in either case. In the motor shown in Figs. 31*a* and 31*b* there are two primary or inducing windings distributed in the stator slots and displaced 90 degrees. Winding

W_1 is connected to phase 1 and winding W_2 is connected to phase 2 of a two-phase supply. The rotor is similar to the armature of a direct-current motor. It is provided with two

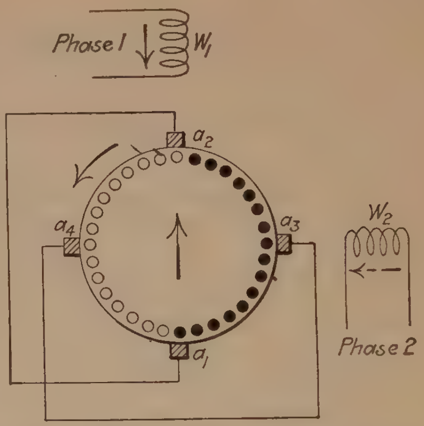


FIG. 31*a*.

Primary form of two-pole two-phase induction motor. Conditions in normal operation at the instant shown:

1. Primary voltage impressed on W_1 is maximum.
2. Load current in W_1 is maximum.
3. Magnetizing current in W_1 is passing through zero.
4. Flux in vertical axis due to magnetizing current in W_1 is passing through zero.
5. Induced voltage at brushes a_1–a_2 is maximum.
6. Induced current through brushes a_1–a_2 is maximum.
7. Primary voltage impressed on W_2 is passing through zero.
8. Load current in W_2 is passing through zero.
9. Magnetizing current in W_2 is maximum.
10. Flux in horizontal axis, due to magnetizing current in W_2 is maximum.
11. Induced voltage at brushes a_3–a_4 is passing through zero.
12. Induced current through brushes a_3–a_4 is passing through zero.
13. Counter voltage at brushes a_1–a_2 generated by cutting flux due to W_2 is maximum.
14. Counter-voltage at brushes a_3–a_4 generated by cutting flux due to W_1 is zero.

Torque is due to reaction of items 6 and 10.

Solid arrows show magnetizing forces due to load current.

Dotted arrows show magnetizing forces due to magnetizing current.

sets of brushes, a_1–a_2 and a_3–a_4, which short-circuit the rotor, in line with the axes of the stator windings.

The voltage in each primary or stator winding W_1 and W_2 causes magnetizing currents to flow in these windings, setting up two fluxes which are in time quadrature with each other due to the fact that the supply voltages are in time quadrature. The alternating flux set up by W_1 induces a voltage in the rotor coils, by transformer action. This voltage appears at brushes a_1–a_2. As these brushes are short-

circuited, a current flows through the rotor conductors and brush circuit as indicated by the dots and circles in Fig. 31*a*. The induced voltage is in quadrature with the flux which

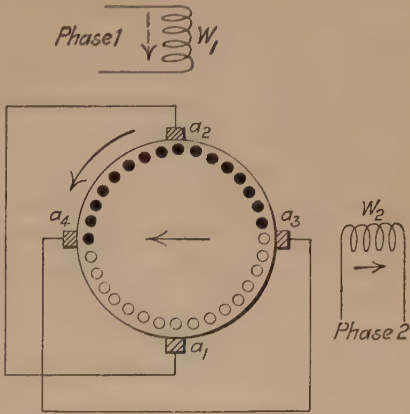


FIG. 31*b*.

One quarter cycle later than shown in 31*a*.

1. Primary voltage impressed on W_1 is passing through zero.
2. Load current in W_1 is passing through zero.
3. Magnetizing current in W_1 is maximum.
4. Flux in vertical axis due to magnetizing current in W_1 is maximum.
5. Induced voltage at brushes a_1–a_2 is passing through zero.
6. Induced current through brushes a_1–a_2 is passing through zero.
7. Primary voltage impressed on W_2 is maximum.
8. Load current in W_2 is maximum.
9. Magnetizing current in W_2 is passing through zero.
10. Flux in horizontal axis due to magnetizing current in W_2 is passing through zero.
11. Induced voltage at brushes a_3–a_4 is maximum.
12. Induced current through brushes a_3–a_4 is maximum.
13. Counter-voltage at brushes a_1–a_2 generated by cutting flux due to W_2 is zero.
14. Counter-voltage at brushes a_3–a_4 generated by cutting flux due to W_1 is maximum.

Torque is due to reaction of items 4 and 12.

induces it, namely the flux due to W_1. In normal operation the current due to this voltage is practically in phase with the latter. It is thus in phase with the flux due to W_2. This current reacts with the flux due to W_2 to create a torque, just as the armature current in a direct-current motor reacts with the field flux to produce torque.

The resistance of the rotor and of its external short-circuit is low as related to the voltage induced in it. If only the resistance and reactance of the rotor were available to restrict the current flow, a heavy current would result. The rotor

conductors rotating in the flux due to W_2, have generated in them a voltage. This generated voltage is in time phase with the flux due to W_2 and therefore in time quadrature with the flux due to W_1. The voltage induced by the flux due to W_1 is in time quadrature with this flux and therefore of same phase as but of opposite sign to the voltage generated by cutting flux due to W_2. This generated voltage thus corresponds to the counter-voltage generated in the conductors of a direct-current armature.

If the rotor of this motor were to revolve at synchronous speed, the counter-voltage generated along each axis would equal the induced voltage along the same axis, hence no current would flow and no torque would be produced. This condition would be identical with that obtaining in a direct-current shunt motor running slightly above its no-load speed when the counter-voltage would equal the impressed armature voltage.

The polyphase induction motor is identical in fundamental theory with the direct-current shunt motor with the difference that the current is conveyed to the rotor inductively instead of conductively and with the further difference that reactance plays a part in the induction motor but not in the direct-current motor.

The magnetizing force due to the induced load current in the rotor (Fig. 31*a*) is along the vertical axis. The induced rotor current is, in normal operation, practically in phase with the induced rotor voltage which is in opposition to the primary voltage impressed on W_1. The induced load current in the rotor tends to set up a magnetic field in time phase with itself. The stator winding W_1 then draws current from the line, in time phase with the supply voltage, sufficient to neutralize the magnetizing influence of the load current in the rotor. Thus the load demand is reflected to the supply system and load current in phase with the supply voltage is drawn from the line. The relations between magnetizing current and primary and secondary load current in this motor are identical with those in the static transformer.

We have considered above only the action with reference to the brushes a_1–a_2. In a similar manner winding W_2 induces

in the rotor conductors a voltage and current indicated by the dots and circles in Fig. 31*b*. This current reacts with the flux due to W_1 to produce torque. Rotation in the flux due to W_1 generates a counter-voltage appearing at brushes a_3–a_4. The action duplicates that previously described.

It will be seen that this two-pole motor has two working axes, one for each phase. This compares with the single working axis per pole pair afforded by the direct-current motor. As the material is utilized along two axes per pole pair in the two-phase induction motor it is used to better advantage than in a direct-current motor. This is the main reason why a polyphase motor can be made lighter than a direct-current motor for the same output.

In normal operation the rotor of the motor illustrated in Figs. 31*a* and 31*b* is rotating at nearly synchronous speed, the rotor impedance is low and the currents flowing in the rotor conductors are practically in phase with the voltage which produces them. These currents are then practically in phase with the fluxes with which they react to produce torque and the operating torque per ampere is high. When the rotor is at rest, the rotor currents lag considerably behind their respective voltages (see page 57). For this reason the ampere-turns in one rotor axis are not in phase with the flux in the other rotor axis and the starting torque per ampere is low. In this respect the polyphase induction motor differs distinctly from the direct-current shunt motor.

The primary form of the two-phase motor just described is not in commercial use because of the far greater simplicity of the equivalent squirrel-cage motor.

Having considered the theory of the polyphase induction motor as the polyphase equivalent of the direct-current shunt motor, establishing the similarity of the polyphase induction motor to both the direct-current shunt motor and the static transformer, we will now take up the more familiar revolving field theory, which applies to the primary form as well as the squirrel-cage form of the polyphase motor.

Revolving Field Theory of Action.—The coils in the primary winding are arranged to produce magnetic poles distributed around the bore. There are two or three separate coil groups

according to the number of phases for which the motor is built. Each group forms a phase winding and is displaced from all others. The poles resulting from one phase winding are angularly displaced from those due to any other phase windings because of the different space locations of the coil groups. Let us consider a two-pole two-phase motor shown diagrammatically in Figs. 32*a*, *b*, *c*, and *d*. Such a machine must carry two-phase primary windings displaced by 90 deg. We will excite phase *A* with direct current. The poles *N–S* are then formed within the bore as shown in Fig. 32*a*. We will next disconnect phase *A* and excite phase *B* with direct current. The poles *N–S* now occur at different points, as shown in Fig. 32*b*. Next we will disconnect phase *B* and again excite phase *A*, but in reversed sense. The poles *N–S* now occur at the original locations but the polarity is reversed as seen in Fig. 32*c*. The magnetism has now shifted or revolved around the bore 180 electrical deg. Next we will disconnect phase *A* and excite phase *B* in reverse sense. The poles *N–S* have now shifted 90 deg. further around the bore as shown by Fig. 32*d*. If we now return to the original exciting connection, we will have caused the axis of the stator magnetization to make one complete revolution around the bore of the stator.

An alternating current continually changes in magnitude and periodically changes in direction, passing through a cycle of values from zero to a maximum and back to zero in each direction. A two-phase current comprises two separate currents of this nature differing in time by one quarter cycle. If we connect the primary windings of our motor to a two-phase supply, one phase to excite group *A*, the other phase to excite group *B*, the following action occurs. When the current in phase *A* is a maximum the current in phase *B* is zero, being one quarter cycle behind or ahead of *A*, according to the generator connections in the supply system. With current in *A* at a maximum the magnetic conditions correspond to Fig. 32*a*. One quarter cycle later the current in phase *A* will drop to zero and that in phase *B* will be at its maximum. The magnetic conditions now correspond to Fig. 32*b*. After an additional quarter cycle the current in phase *A* will again be a maximum but flowing in the opposite direction. The

magnetic conditions now correspond to Fig. 32*c*. After an additional quarter cycle the current in phase *B* is reversed and at a maximum. The magnetic conditions are as in Fig. 32*d*. Completion of the cycle reinstates the initial conditions shown

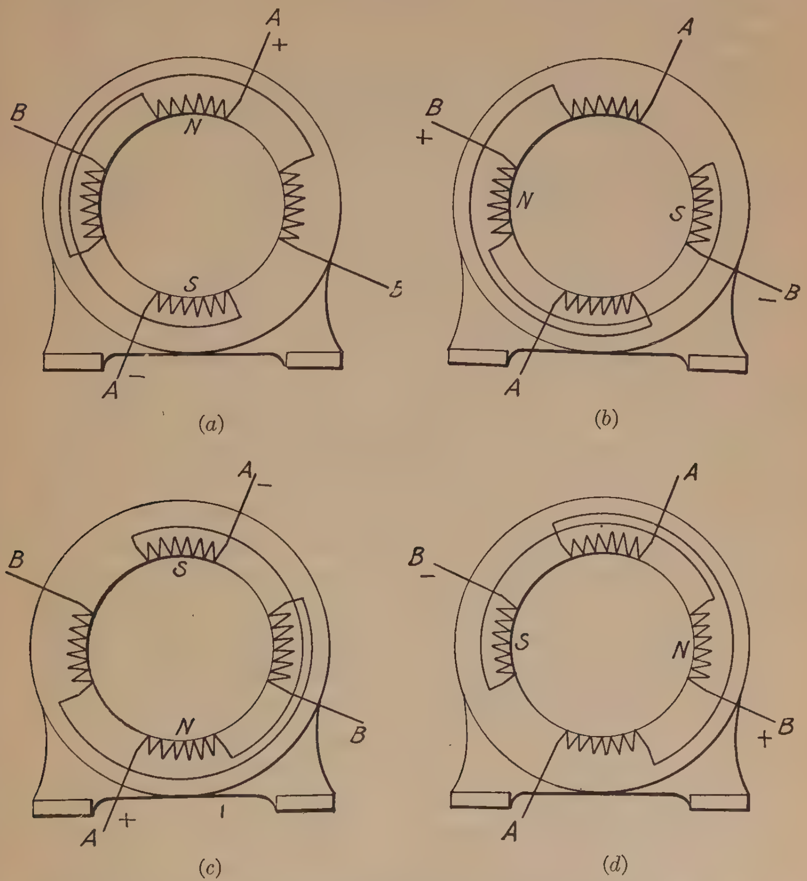


FIG. 32 *a*, *b*, *c*, *d*.—Arrangement of stator windings in a two-pole, two-phase motor.

in Fig. 32*a*. It will be seen that, through the agency of two-phase alternating currents passing through coils displaced by 90 deg., the axis of the stator magnetization of this two-pole motor has been caused to rotate once about the bore during

one cycle of the supply. Similar conditions hold for three-phase current, the phases being displaced 60 deg. from each other instead of 90 deg. The resulting magnetic field due to polyphase currents in suitably arranged windings shifts progressively around the bore just as if the field axis were rotated mechanically.

Production of Torque.—The secondary or rotor of a polyphase induction motor carries windings connected to form closed circuits. The rotor is placed within the bore of the stator. When polyphase alternating current is applied to the stator windings, a revolving field is set up. If the rotor stands still, its conductors are cut by the magnetic lines of the revolving field. The relative motion between this flux and the rotor conductors generates a rotor voltage which forces a current to flow through the secondary or rotor conductors. The ampere-turns due to this current co-operate with the revolving field to produce the torque of the motor. This torque causes the rotor to revolve in the direction of the revolving field. So long as the motor revolves less rapidly than the revolving field, its conductors will cut magnetic lines and will thus have current generated in them. The faster the rotor revolves the less will be the rate at which its conductors cut the lines of the revolving field and the lower the voltage and current generated in them. At synchronism there is no relative motion between the revolving field and the rotor conductors, therefore no rotor current and no torque. In practice this speed is never reached because, even at no-load, the motor must exert a small torque in order to overcome friction and windage losses. The difference between the speed of the revolving field of the motor and the speed of the rotor is referred to as "slip." Near synchronism, the greater the slip, the greater the torque. Thus, as load is placed upon the shaft of an induction motor, the rotor drops slightly in speed so that more magnetic lines may be cut, more voltage generated, more current passed and enough torque produced to meet the demands of the load.

Determination of Speed.—While the current passes through a complete cycle, the magnetism rotates through 360 magnetic deg. or two polar arcs. This relation holds true no matter how many polar groups there may be on the stator. Consider

a 60-cycle current impressed upon the windings of a six-pole motor. During each cycle the field will shift over two polar-arcs or one-third of the circumference. Hence, the total speed of rotation will be 60 divided by 3 or 20 revolutions per second or 1,200 revolutions per minute. In general, the speed, in revolutions per minute, equals cycles times 120 divided by the number of poles. The speed at which the revolving field rotates is called the synchronous speed of a motor. The lag of the rotor below synchronous speed is called the slip. Slip is expressed in per cent of synchronous speed. A motor having a synchronous speed of 1,200 r.p.m. and running at 1,140 r.p.m. under full load has a 5 per cent slip at that load. An induction motor can never attain synchronous speed although it will approach it at no-load. Synchronous speed of an induction motor corresponds to that speed of a direct-current shunt motor which would make the counter-voltage equal to the impressed voltage.

Current Relations.—In a two-phase motor the two leads of each phase winding are connected to the two line wires of each phase of the supply system. In three-phase motors the phase windings are commonly grouped in one of two connections called the star or delta connections. In any case the primary windings form closed circuits from one line wire to another. The conductors in these windings must be large enough to carry the load current of the motor. The resistance of the windings is low and is not sufficient to prevent a heavy flow of current with the phase terminals connected across the line. The flow of current is limited, not by the resistance of the windings, but by self-induction.

A conductor in a magnetic field of varying intensity has induced in it a voltage. This voltage opposes that which drives the current setting up the varying magnetic field. In the case of the primary windings of our motor, the alternating current causes in the individual phase windings and coils a magnetism which is continually changing in magnitude and reversing. A counter-voltage is therefore set up in these same windings. This counter-voltage opposes the impressed voltage but is always a little less than the latter. Because of the voltage difference, a current flows through the primary winding

sufficient to maintain the magnetism and retain equilibrium. The primary current is thus restricted through induced counter-voltage in much the same way that load current in a direct-current armature is restricted by generated counter-voltage.

Magnetizing Current.—The primary current necessary to set up the flux is called the magnetizing current. The primary current taken at no-load is largely magnetizing current as the load current in rotor and stator is then very small. The magnetizing current is approximately constant for all loads. It is a wattless current in quadrature with the impressed voltage.

The magnetizing current required by slow-speed motors having a large number of poles is greater than that taken by high-speed motors having few poles. In general, the magnetizing current for standard polyphase induction motors ranges from 25 to 60 per cent of full-load current, depending primarily upon the speed, as above outlined.

Primary and Secondary Current.—The rotor currents which produce torque are due to the slip voltage which, in turn, is due to cutting the revolving field flux. The slip voltage is a generated voltage and is in phase with the revolving field flux. Referring to Fig. 33, let us consider the instant when the axis of the revolving flux is vertical. The flux due to W_1 is then at its maximum, and is, for the time being, the only component of the revolving flux. The voltage generated in the rotor due to cutting this flux is then so distributed as to cause load currents to flow as indicated by the dots and circles. These currents have a magnetizing force along the horizontal axis in line with winding W_2. In order to offset or neutralize the magnetizing force due to the load current in the rotor, a corresponding current must flow in W_2. The rotor load current is, in normal operation, in phase with the generated rotor voltage and with the revolving flux and therefore in quadrature with the voltage impressed on W_1. To neutralize this rotor magnetization due to the rotor load current the winding W_2 must carry a primary current in quadrature with the voltage impressed on W_1 and therefore in phase with that impressed on W_2. This current therefore represents power intake. Similar conditions occur at other instants with respect to phase 1. Thus it is evident that load currents in the rotor act induct-

ively to cause power to be drawn from the supply system. As the mechanical load increases, the rotor slows down, increasing its slip, slip voltage and current. The effect of

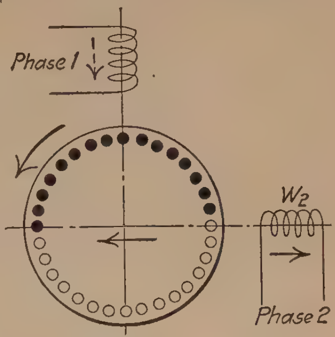


FIG. 33.

Two-phase, two-pole induction motor, showing reflection of load demand to the supply system.

Conditions in normal operation at the instant shown:

1. Primary voltage impressed on W_1 is passing through zero.

2. Primary load current in W_1 is passing through zero.

3. Magnetizing current in W_1 is maximum.

4. Flux in vertical axis, due to magnetizing current in W_1, is maximum.

5. Slip voltage is maximum in conductors located on vertical axis, cutting maximum flux.

6. Rotor load current, set up by slip voltage, is indicated by dots and circles.

7. Primary voltage impressed on W_2 is maximum.

8. Primary load current in W_2 is maximum.

9. Magnetizing current in W_2 is passing through zero.

10. Magnetizing force of rotor load current is horizontal and neutralized by opposing force of load current in W_2.

11. Torque is due to rotor currents indicated, in co-operation with the vertical flux.

Solid arrows show magnetizing forces due to load current.

Dotted arrows show magnetizing forces due to magnetizing current.

increased load current in the rotor is counteracted by a corresponding increase in primary current. Thus the load demand is supplied from the power source. The relations of load current and magnetizing current are discussed further in the paragraphs referring to power-factor.

Summary of Action.—The fundamentals of polyphase induction motor action may now be briefly summarized. Polyphase alternating currents flowing through suitably grouped primary coils (stator) set up a revolving field. Polyphase currents are generated in the secondary conductors (rotor) because of their relative motion with respect to the revolving field. These currents produce the motor torque in conjunction with the revolving field. By transformer action these rotor currents, which are

proportional to the load, are reflected in the primary, the latter drawing a corresponding amount of current from the line.

Effect of Rotor Resistance.—As the secondary voltage is that which drives the secondary currents through the rotor windings, it follows that its value for a given current, *i.e.*, torque, must depend upon the resistance and reactance of these windings. A larger resistance demands a larger voltage for the required current and therefore a higher rate of cutting of magnetic lines or a greater slip. If the torque requirement is

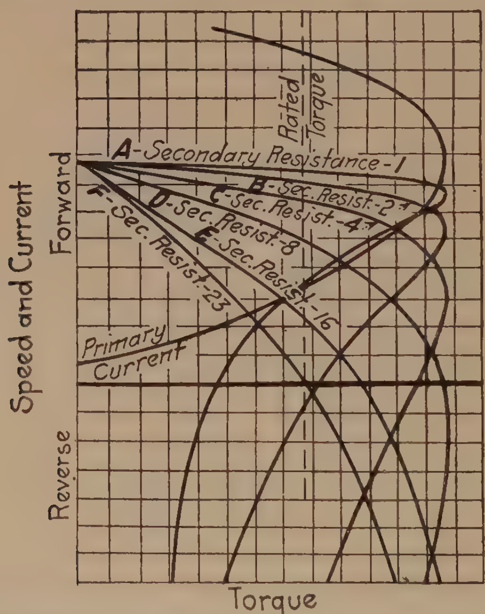


Fig. 34.—Speed-torque and current curves of a polyphase induction motor with different values of secondary resistance.

constant, any variation in the secondary resistance requires a proportionate variation in the slip. If the slip with a given torque is 10 per cent, for instance, it must be 20 per cent for double the resistance. The secondary resistance may be in the windings themselves, or it may be entirely separate from the machine and connected to the windings by suitable means.

Figure 34 shows speed-torque curves for a motor with a number of different values of resistance in the secondary cir-

cuit. Curve *A* is obtained when the secondary resistance is very small and only a slight increase in slip is necessary to produce a material increase in rotor current with increased load. If the secondary circuit resistance be doubled, the slip for a given torque is doubled. Curve *B* results with secondary resistance double that of curve *A*. In curve *C* the resistance is again doubled. Curve *D* applies to a motor having a relatively high resistance in the secondary circuit.

Maximum Torque.—A number of factors are involved which tend to restrict the torque developed under heavy loads. One of these is the resistance of the primary windings. The primary resistance drop causes a decrease in the primary counter-voltage required. As a consequence, the primary flux decreases somewhat under load, thus reducing the torque per ampere of rotor current and requiring a greater rotor slip.

Influence of Magnetic Leakage.—It has been previously stated that the magnetizing influence of the secondary current is opposed to that of the primary. Largely as a result of this opposition some "leakage flux" passes between the primary and secondary windings without interlinking them. This "leakage" reduces the effective, torque-producing flux. This leakage is most pronounced at heavy loads and is a factor which limits the torque-producing ability of the motor.

Causes of Stalling.—The current in the rotor conductors, with light loads and small slip, is practically in phase with the voltage generated in these conductors due to slip. The impedance of the secondary circuit is then almost entirely resistance as the frequency of the rotor current is very low when the slip is small. As the load comes on and the slip increases, the frequency of the rotor current increases. This increases the leakage reactance of the secondary circuit proportionately. As the reactance increases, the secondary current lags more and more behind both the secondary voltage and the flux. The torque-producing effectiveness of the rotor current on the flux is thus diminished. As the load is increased, a point is finally reached where the lag of the secondary current increases faster than the magnitude of said current with the result that the torque diminishes in spite of the continuously increasing secondary current and the motor stops.

Speed at Which Maximum Torque Is Developed.—For reasons above mentioned, every induction motor has a maximum torque value at which it will "pull out" or stall. An inspection of Fig. 34 shows that the pull-out torque value is independent of the amount of secondary resistance. The speed at which maximum torque value is reached, however, depends upon the secondary resistance value. If the secondary resistance be low, a relatively small amount of reactance exerts proportionately more influence, and vice versa. Thus a motor with low resistance secondary will sustain its speed quite closely until the pull-out point is reached while a motor with high secondary resistance will slow down decidedly with heavy overloads and the pull-out point will occur at a relatively low speed.

Value of Maximum Torque.—The maximum or pull-out torque of a polyphase induction motor depends upon its design, which in turn is adapted to its intended usage. Thus a motor intended for crane and hoist duty will have a relatively high maximum torque. High-speed motors tend to have somewhat higher maximum torques than low-speed motors and 25-cycle motors are, in general, superior to 60-cycle motors in this respect. Pull-out torque values usually range from two to three and one-half times full-load rating.

Influence of Primary Voltage.—At this point mention may well be made concerning the influence of primary voltage on torque production. Primary voltage has a double influence. An increase of impressed voltage requires a corresponding increase of induced counter-voltage. This can be brought about only by increased flux. Increased flux, in turn, causes increased secondary voltage to be generated for any given value of slip, thus causing increased secondary current. Since both the flux and the secondary current are increased, the torque is doubly affected. Both the maximum torque and the starting torque of a motor are proportionate to the square of the primary voltage impressed. For example, a drop of 10 per cent in voltage reduces the maximum torque which a motor can develop to 81 per cent of that which it could develop at normal voltage. Since voltage has such a marked influence on torque capacity, it is desirable that well-loaded motors which may be subject to voltage variation have liberal pull-out torques.

Starting Torque.—The starting torque of a polyphase induction motor is affected by much the same factors as the maximum torque but as applied to the stationary condition of the rotor. The starting torque is proportional to the square of the impressed voltage. It is directly proportional to the rotor resistance and inversely proportional to the square of the total impedance of the motor. The impedance is made up of resistance and reactance components, hence a change in rotor resistance affects the starting torque both directly and indirectly. So long as the rotor resistance is the lesser item in the impedance, an increase of rotor resistance results in an increase in starting torque. Beyond this point the inverse relation is greater than the direct relation and increased rotor resistance then causes decreased torque at starting. The reactance component of the impedance depends upon the magnetic leakage. If high starting torque is desired, the magnetic leakage should be as small as possible.

The effect of rotor resistance on starting torque is evidenced in Fig. 34. The standstill torque of curve *A* is relatively low, this curve applying to the case of low rotor resistance. As the rotor resistance is increased, as shown in curves *B* and *C*, the starting torque is improved. Curve *D* represents the conditions existing when the rotor resistance is of such a value as to cause maximum torque to be exerted at standstill. If the rotor resistance is still further increased, such a curve as *E* results; the starting torque will diminish. There is thus one definite value of rotor resistance, other conditions being equal, which will develop maximum starting torque.

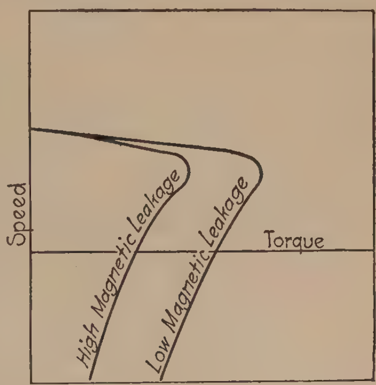


Fig. 35.—Speed-torque curves of polyphase induction motors, showing effect of magnetic leakage.

The effect of magnetic leakage on pull-out torque and starting torque is illustrated in Fig. 35, which shows the

relative curves of two similar motors having different values of magnetic leakage.

Primary Current Relations.—The primary current relations corresponding to the various torque relations already discussed, may be most readily shown by means of the primary-current-torque curve in Fig. 34. This curve is the same for all the speed-torque curves A, B, C, D, E, and F. Beginning at the point of no-load or zero torque, the curve rises quite uniformly until maximum torque is approached. Beyond this the primary current increases at a different rate as the motor slows down and stalls. The upper portion of the curve corresponds to the starting period. Comparing the starting currents corresponding to the different static torques, it will be seen that the starting current corresponding to curve A is very high, even though low torque is produced. The torque per ampere is low. Curve B indicates a lower starting current and gives more torque. The torque per ampere is higher. Curve C takes less starting current than B and yields a higher torque. Curve D takes less starting current than C and delivers maximum torque at standstill. The torque per ampere is a maximum. Curve E takes less starting current than D but delivers a reduced starting torque. From these curves it is evident that a high resistance in the rotor circuit gives the highest starting torque with the least current demand. For a given running torque there is no difference as far as current is concerned, all the curves having the same current for a given torque, but operating at different speeds.

Torque per Ampere at Starting.—The maximum running torque of a motor with low resistance in the rotor circuit is considerably greater than the starting torque although the starting current exceeds the current at maximum torque. This is in part due to the fact that, at starting, the effective flux is greatly reduced by magnetic leakage. Also, at high rotor frequencies corresponding to low rotor speeds the rotor power factor is low and the rotor current is out of phase with the torque-producing flux. As the rotor power-factor is affected by the rotor resistance, conditions at starting are improved as the rotor resistance is increased.

Current Relations when "Plugging."—The direction of rota-

tion of a polyphase induction motor is reversed by reversing the rotation of the revolving field. This is accomplished by reversing one phase of a two-phase motor or by interchanging any two primary leads of a three-phase motor. It may be noted that the speed-torque curves of Fig. 34 extend below the line of zero speed. The portions below this line represent conditions existing when the motor is "plugged" by reversing the rotating field while the motor is running. Here it may be seen that, if a motor with low-resistance rotor, such as represented by curve A, be plugged at full speed, the current is not much higher than the starting current and the torque is somewhat less. If the secondary resistance be high and the characteristic be such as shown in curve E, both the plugging current and torque are greater than standstill values. If provision be made for adjustment of the secondary resistance of a motor subject to reversing service it is desirable that a value even higher than that indicated by curve E be inserted to restrict the plugging current and torque, this resistance being decreased as the motor stops and accelerates in the reverse direction.

Influence of Frequency and Voltage.—The synchronous speed of a polyphase motor is dependent upon but one external factor, namely, frequency. The actual speed is dependent upon the synchronous speed and the slip. One of the factors influencing the slip is the primary voltage. A drop in voltage decreases the torque-producing ability of the motor per rotor ampere-turn and this necessitates increased slip. The slip varies approximately as the inverse square of the voltage. A motor having a synchronous speed of 1,200 r.p.m. and a 5 per cent slip at normal voltage will run at 1,140 r.p.m. If the voltage drop to 90 per cent of normal, the speed, with the same load, will drop to 1,126 r.p.m. Thus although primary voltage variation does not have a direct bearing or a marked influence on motor speed, it does affect it indirectly and in a minor degree. The effect of voltage on torque has been previously mentioned. The operation of a motor on 10 per cent over-voltage increases its maximum torque 21 per cent. It increases the magnetizing current and lowers the power factor. It increases the iron loss but this is largely compensated for by decreased copper loss.

Since the synchronous speed is determined by the frequency, any change in frequency has a direct and proportionate influence on the speed. It has a further effect in that an increase of frequency enables a lesser primary flux to induce the required counter-voltage, thus diminishing the torque-producing flux and increasing the slip. In its indirect effects an increase in frequency is similar to a decrease in voltage.

Efficiency.—The efficiency of a polyphase induction motor, as with any other machine, is the ratio of power developed to power expended. It is represented by the ratio:

$$\frac{\text{output}}{\text{output}+\text{losses}}.$$

The losses in an induction motor comprise the resistance losses in rotor and stator, the iron core losses, the friction and windage.

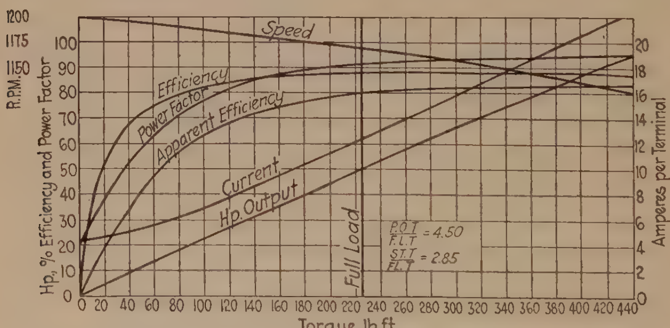


FIG. 36.—Characteristic curves of typical polyphase squirrel-cage induction motor.

The shape of the efficiency curve is determined by the relative values of different losses. A motor having large resistance losses will show relatively high efficiency at fractional loads, with lower efficiency at overloads, the reverse being true for a motor having relatively smaller resistance losses. Thus a motor with a low-resistance rotor will be more efficient on heavy loads than one having a rotor of higher resistance. In general the efficiency is proportionate to the expression "1-slip," the slip being expressed as a decimal.

The efficiency of a high-speed induction motor is usually

somewhat higher than that of a low-speed motor of the same horsepower rating. As a lower torque is required at high speed the copper losses and iron losses are reduced. The friction

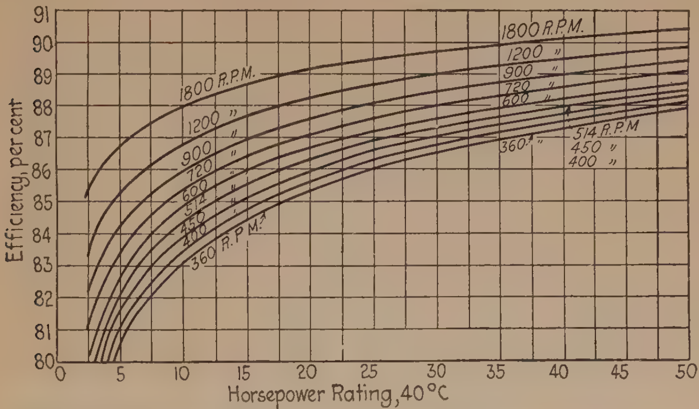
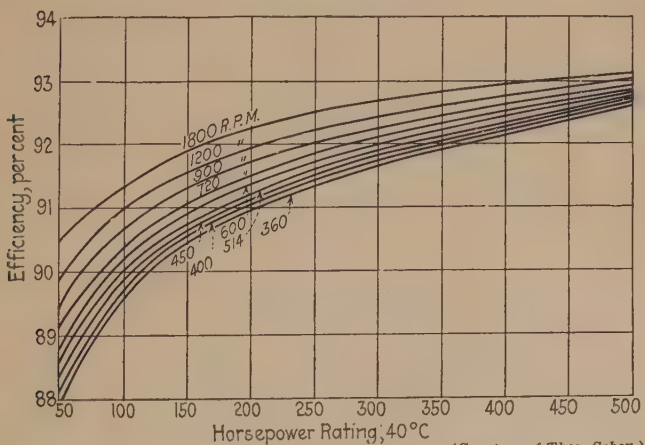


FIG. 37.—Full-load efficiencies of 60-cycle polyphase squirrel-cage induction motors.



(Courtesy of Theo. Schon.)

FIG. 38.—Full-load efficiencies of 60-cycle polyphase squirrel-cage induction motors.

and windage losses are relatively higher but do not offset the gain. The general shape of the efficiency curve may be seen from Fig. 36. In Figs. 37 and 38 are shown the full-load efficiencies of a line of 60-cycle squirrel-cage induction motors.

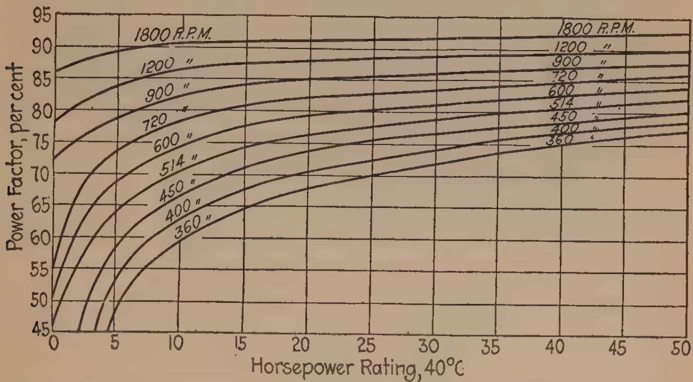
Power Factor.—The current in the motor primary may be considered as composed of two components, one in phase with the voltage and one a quarter-cycle out of phase. The current in phase with the voltage is the work current and supplies power. The lagging current is that which magnetizes the iron. That it does no work may be seen by the following consideration. When this current is magnetizing the iron to a given polarity, it is storing energy in the iron. Voltage and current are of the same sign, work is being done and power withdrawn from the line. This covers a quarter-cycle. During the next quarter-cycle the current falls to zero and the magnetism falls to zero also, returning its stored energy to the line. During this period current and voltage have opposite signs, and the work done is negative. At the end of a half-cycle the net power input is zero. The other half of the cycle is a repetition of the first half. Thus the magnetizing current really does no work in that it does not contribute to the output at the motor shaft nor is any material part of the energy it represents converted into heat. The iron losses due to frequent reversals of magnetism are in the nature of an energy load and involve a small current component in phase with the voltage.

Power Factor at Starting.—The power factor during the starting period may be an item, particularly in the case of frequently started motors. The power factor at the instant of starting a polyphase induction motor is approximately the ratio of the sum of the resistances of rotor and stator windings to the total impedance. It is thus evident that a low reactance (magnetic leakage) and a high resistance are contributory to a good power factor at starting. With a given reactance, the higher the resistance the better the power factor. A motor with large rotor resistance has relatively high power factor while starting. It is again evident why a motor with high-resistance rotor gives greater starting torque per ampere input than one with low-resistance rotor. The current in the former machine is more nearly in phase with the voltage and is thus of greater torque-producing utility.

Influence of Design.—As stated, the power factor of a motor depends upon the magnetizing current and the magnetic leakage. The value of magnetizing current depends largely upon

the length of the air gap and the magnetic density therein. High magnetic density is contributary to good starting and overload torques but detrimental to power factor. Magnetic leakage depends materially upon the length of the air gap and the shape of the teeth. A short air gap, mechanically undesirable, is beneficial to power factor. Closed or semi-closed slots, also undesirable from a construction point of view, are also helpful in securing a high power factor. Any design must be a compromise between opposing demands.

Effect of Load.—The power factor of a polyphase induction motor is very low at light loads since most of the current then



(*Courtesy of Theo. Schon.*)

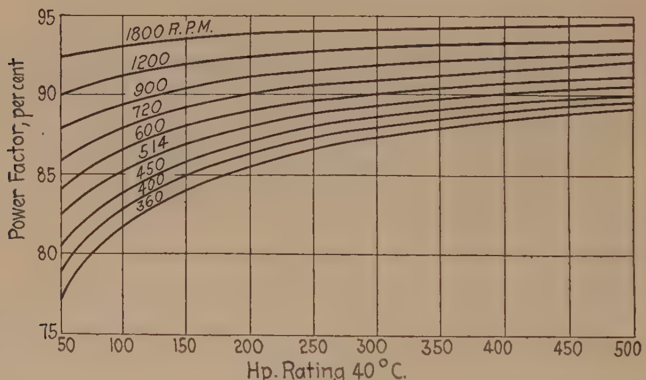
Fig. 39.—Full-load power factor of 60-cycle polyphase squirrel-cage induction motors.

taken from the line is wattless and is required to magnetize the structure. The magnetizing current remains nearly the same at all loads. The energy component of current increases with the load. Hence, the power factor (ratio of energy current to total current) also increases with load. Figure 36 includes a typical load power-factor curve.

It may well be noted that an ammeter, which measures resultant primary current, does not give a true indication of motor load. Thus, if the magnetizing current of a motor is 40 per cent of full-load current, the ammeter will indicate a little more than 40 per cent full-load amperes with no mechanical load on the motor. As load is applied, the primary current will

increase and will approach the primary voltage in phase but the current will not be proportionate to the load. An ammeter can be used for load determination only in connection with efficiency and power-factor curves for the motor in question, properly corrected for any voltage differences. Power input can be measured only by the use of a polyphase wattmeter or by a combination of single-phase wattmeter readings.

Speed and Frequency Effects.—The power factor of slow-speed motors is lower than that of high-speed motors, since the low-speed motor has a larger frame and more poles to mag-



(*Courtesy of Theo. Schon.*)

FIG. 40.—Full-load power factor of 60-cycle polyphase squirrel-cage induction motors.

netize. The twenty-five cycle motor, having fewer poles than the sixty-cycle motor for a given speed, requires less magnetizing current and has a somewhat better power factor. This advantage is particularly pronounced at very low speeds. Figures 9 and 10 show the full-load power factor values for a typical line of sixty-cycle, squirrel-cage induction motors.

Apparent Efficiency.—"Apparent efficiency" is the product of efficiency and power factor. It is the ratio of watts output to volt amperes input. Its value determines the actual capacity of lines and transformers necessary for supplying the motor. A curve of "apparent efficiency" is included in Fig. 36.

THE SQUIRREL-CAGE MOTOR

Polyphase induction motors comprise two main types distinguished by the design of the rotor windings. The more common type is the squirrel-cage motor. The secondary winding of the ordinary squirrel-cage motor consists of bars passing through the rotor slots with their ends connected to short-circuiting rings. The name is derived from the resemblance to a squirrel cage (see Fig. 41).

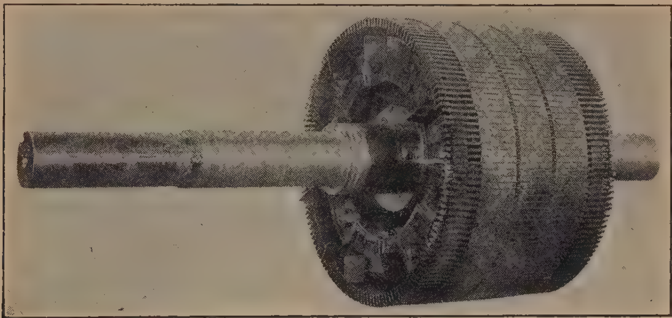


Fig. 41.—Squirrel-cage rotor.

Speed Characteristic.—The synchronous speed of an induction motor, depending upon the frequency and the number of pole groups in the primary winding, is fixed and is practically constant. The actual speed is less than the synchronous speed by the amount of the slip. In a squirrel-cage motor the resistance of the secondary windings is usually low. A small slip then gives rise to a large rotor current and torque. The drop in speed occasioned by load is small. Figure 36 shows the characteristics of a squirrel-cage motor. The performance of motors of this type is also represented by curves *A* and *B*, Fig. 34. The operating characteristics are quite similar to those of the shunt-wound direct-current motor. The ordinary squirrel-cage motor has a speed regulation of 3 to 5 per cent from no-load to full-load. Induction motor speed is but slightly affected by temperature, the hot speed being slightly less than the cold value.

Starting Performance.—Slow-speed squirrel-cage motors will develop in starting about 125 per cent of full-load torque and high-speed motors up to 250 per cent full-load torque if

full voltage is applied to the primary. The corresponding current at starting would be six to seven times full-load current. The starting current of a squirrel-cage induction motor depends upon the voltage impressed at the primary terminals and is independent of the torque against which the motor is to start. The current inrush at starting is usually of short duration as the current falls quickly to a running value as the motor accelerates. The duration of the starting period depends upon the nature of the load to be accelerated. It is desirable that the current at starting be no greater than necessary. Since the initial rush of current is controlled by the impressed voltage, this voltage may well be reduced to a point such that it is only sufficient to start the load, with a safe margin for variable conditions. For example: let it be desired to secure, at starting, full-load torque from a motor which will deliver 250 per cent full-load torque at standstill with full voltage impressed. The proper starting voltage would equal

$$\text{Line volts} \times \sqrt{\frac{1}{2.5}} = 0.63 \text{ line volts.}$$

About 66 per cent full voltage should be impressed. If a higher voltage be used little is gained in performance but a considerably higher current inrush results. If, however, the required torque at starting were 125 per cent full-load torque, a higher voltage must be impressed in order that sufficient torque may be developed at standstill to start the load.

Small motors up to and including 5 hp. are ordinarily started by connection directly across the line. Not infrequently somewhat larger motors are started in this manner. As a usual practice, larger motors of the squirrel-cage type are started under reduced voltage. This is most frequently obtained by means of auto-transformers and some type of double-throw switch for connecting the motor first to the low-voltage leads and subsequently to the line. The transformers are provided with several taps enabling the user to select any one of a number of starting voltages. The starting current is greatly reduced by this practice, which is more fully discussed in Chap. XVI.

General Performance.—The great advantage of the squirrel-cage induction motor is its simplicity. It has neither commu-

tator, collector rings nor brushes. The only wearing surfaces are the bearings. A more simple machine mechanically could not be desired. This simplicity begets ruggedness, reliability and freedom from trouble. The efficiency of the squirrel-cage motor is good. The losses in the iron are quite constant at all loads, as are also the bearing and windage losses. The copper loss alone increases materially with the load. Since the resistance of the rotor is low, the copper losses are not great and the efficiency of this type of induction motor is particularly good at full load and overloads. The squirrel-cage motor is excellently adapted for all classes of constant speed drives which require moderate starting and running torques and where starting is infrequent. The great majority of fixed speed drives fall in this class. Because of its simplicity and lower first cost, the squirrel-cage motor is generally preferred to the direct-current shunt motor for constant speed duty.

Rotor Resistance.—In the small and moderate sizes it is possible and feasible to construct squirrel-cage motors having quite high rotor resistance. Such motors have a characteristic similar to curves B or C, Fig. 34. They afford high starting torque and rapid acceleration and may be used to advantage where starting conditions are somewhat severe. They are less efficient and are therefore not well adapted for steady, heavy loads. Motors having sufficient rotor resistance to give 15 to 20 per cent slip at full load may be connected directly across the line in starting. This affords extreme simplicity of control. Motors of this type are often used for elevator service and crane service. The simplicity of control and connections is of particular advantage in crane service where current-collecting devices are involved. Motors having 7 to 12 per cent slip at full load find frequent applications on small presses and shears and similar applications where a drooping speed characteristic is desired in connection with a flywheel. These motors are also used for starting loads having considerable inertia, such as laundry centrifugals. In many respects, these motors are similar to compound-wound direct-current motors. They are better suited for intermittent service than for steady loading because of the lower efficiency and the greater heat to be dissipated in the rotor.

THE WOUND-ROTOR MOTOR

It has been demonstrated that a polyphase motor with high-resistance rotor delivers a greater starting torque per ampere input than a motor with a low-resistance rotor. Consequently, high rotor resistance renders a motor capable of starting heavier loads or with lesser currents. On the other hand the efficiency of a motor with high-resistance rotor circuit is comparatively poor under load conditions. Most of the loss occurs in the rotor resistance. Since the rotor can dissipate but a moderate amount of heat it becomes necessary to pro-

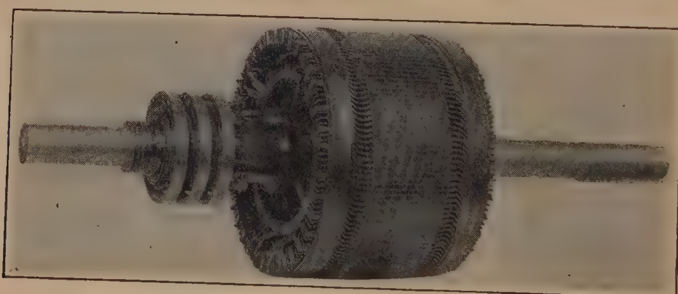


Fig. 42.—Phase-wound rotor.

vide resistors external to the motor and to connect the rotor winding thereto through slip-rings and brushes. Moreover with this arrangement it becomes possible to vary the external resistor by means of a controller and to short-circuit the external resistor altogether, if desired, after the motor has attained running speed. Rotors of this type are provided with windings similar to those on the stator, the terminals of these windings being connected to collector rings. This type of motor is designated as a wound-rotor or slip-ring motor. A phase-wound rotor is shown in Fig. 42.

Rotor Winding.—Motors of this type usually have three-phase secondary windings, irrespective of the number of phases on the primary. The polyphase stator winding creates a uniformly revolving field. It is then possible to use any number of phases desired in the rotor just as the rotating field alternator may be connected for any number of phases. How-

ever, the windings on the rotor must be grouped to produce poles corresponding in number and location to the poles of the stator. In the squirrel-cage winding this effect is obtained automatically although the rotor winding is not arranged with definite pole grouping. It has been found that the characteristics of the wound-rotor motor are improved by increasing the number of phases in the secondary winding. The squirrel-cage winding is, in effect, a multiphase winding. Three-phase windings are used for wound-rotor motors because they require but three collector rings. Single-phase windings would require two rings only but would afford much poorer performance. An increase above three phases is not justified as the improvement is insufficient to offset the added complexity of motor, control and wiring. The star connection is used exclusively for rotor windings as it yields the highest rotor voltage for a given number of rotor conductors and adapts itself readily to the insertion of external resistors in the secondary circuits.

Secondary Voltage.—As the secondary circuit of the wound-rotor motor is connected to resistors and is independent, any desired voltage may be employed. This voltage depends upon the number of turns and the arrangement of the coils in the secondary winding. It is independent of the primary voltage rating so that similar motors differing only in primary voltage may have and commonly do have duplicate rotors. This minimizes the number of different rotors required for a complete line of motor ratings. The secondary voltages used are a compromise. High voltage gives low current, thus minimizing the current carried by the rotor controller, but the voltage must be restricted for reasons of safety and insulation. The voltage used depends materially on the motor size. Small motors are wound for lower voltages and large motors for higher voltages. Different makers differ in their practice. There are no standard secondary voltages.

Secondary Current.—The term "locked secondary volts" is commonly used to designate the voltage between the collector rings of a wound-rotor motor with the rotor stationary. This voltage depends on the transformer ratio between the primary and secondary windings of the motor. Knowing the

locked secondary volts, the secondary current for rated output may be closely approximated from the formula:

$$\text{Secondary Amperes} = \frac{746 \times \text{hp. output}}{\text{Locked sec. volts} \times (1\text{-slip}) \times \sqrt{3}}$$

where horsepower output is full-load rating and slip refers to full-load and rated speed.

Reversal of Rotation.—When the rotation of a wound-rotor induction motor is reversed it is not necessary to change the secondary leads. The primary determines the direction of the revolving field. The rotor winding simply acts as a generator and follows the direction of the revolving field. The fact that the phase rotation in the rotor windings is changed is ordinarily of no consequence since the collector rings are usually connected only to resistors, which are not affected by the phase rotation.

General Performance.—The polyphase wound-rotor induction motor is similar in general characteristics to the shunt-wound direct-current motor with regulating resistance in the armature circuit. At starting it produces about full-load torque with about full-load current input. When running with secondary resistance in circuit its speed varies with the load as does that of a direct-current shunt-wound motor with regulating resistance in the armature circuit. The amount of this variation depends upon the rotor-circuit resistance. Characteristics similar to A, B, C, D, E, or F of Fig. 34 may be secured, according to the secondary resistance used. It is customary to start a motor of this type with high resistance in the rotor circuit and to operate it with lesser resistance in circuit or with all the external resistors short-circuited. A second point of similarity with the direct-current shunt-wound motor lies in the fact that the no-load speed is limited. In this respect the wound-rotor induction motor differs radically from the direct-current series motor. Since the wound-rotor motor is sometimes used for work otherwise handled by the direct-current series motor, this point of difference is important and should be kept in mind.

Efficiency.—The polyphase wound-rotor motor does not materially differ from the direct-current shunt-wound motor

in respect to efficiency. Both are highly efficient at all loads as long as no speed regulation is attempted. The wound-rotor motor with drooping characteristic is quite inefficient. The losses in the secondary resistors lower the efficiency under load materially and to the same extent as regulating resistors inserted in the armature circuit of a direct-current shunt motor. Brush and collector ring losses also lower the efficiency of motors of this type, these losses being from 1 to 3 per cent, according to size, speed and load. The degree to which the efficiency of a wound-rotor motor falls off under load depends upon the amount of resistance in the rotor circuit. Since this resistance is in most cases adjustable, the running position selected decides the characteristics obtained. Where the wound-rotor motor is selected primarily because of its superior starting performance, it is usual to short-circuit all the external resistance as the motor accelerates. If all the external resistance be short-circuited, the motor partakes very closely of the running characteristics of a squirrel-cage motor.

Power Factor.—The power factor of a wound-rotor induction motor is similar to that of the squirrel-cage type but varies with the torque developed rather than the horsepower output. When the wound-rotor motor is operated at reduced speeds with secondary resistance in circuit, the power factor is favorably affected by the secondary resistance losses which represent energy input. The power factor at reduced speed and low horsepower output may be quite high. The power factor in starting a wound-rotor motor is much higher than in starting a squirrel-cage motor and the torque per ampere input is materially higher as previously explained.

Phase Advancer.—It is possible to improve the power factor of a wound-rotor induction motor by introducing into the secondary circuit a magnetizing current supplied by a small machine termed a phase advancer. This machine has an armature and commutator similar to that of a direct-current motor. The stator has a smooth iron core without windings. The secondary leads of the main motor are connected to the brushes of the phase advancer, the armature windings of the latter completing the Y of the secondary circuit. The secondary current, passing through the armature windings has a mag-

netizing influence comparable to the armature reaction magnetization in a direct-current motor. These currents set up a field which rotates in space at a speed corresponding to the slip frequency. (Due to the commutator this field is independent of the mechanical rotation of the armature. In a direct-current motor the armature reaction field, due to continuous current, is fixed in space.) The armature of the phase advancer may be driven by the main motor or by other means. Due to rotation of the armature conductors in the above-mentioned field, voltages are generated of such phase as to cause the flow of magnetizing current components which improve the power factor of the motor. In effect, magnetization is supplied by the phase advancer at some expense of mechanical efficiency. These equipments are not in general use.

Applicability.—The polyphase wound-rotor induction motor is used for frequent starting duty or where high starting torque or moderate starting torque with low current input is desired. Because heavy starting currents are more objectionable with large motors, the wound rotor finds more frequent use in the larger units. As the operating characteristics of the wound-rotor motor with adjustable rotor resistance are not unlike those of the compound-wound or series-wound direct-current motor except as to efficiency, it is sometimes used for service to which those types are applicable. The wound-rotor motor is well adapted for use on a peaked load in connection with a flywheel. It is considerably used for elevators, cranes and hoists and similar manipulating duty under continuous manual control. Its use for adjustable speed service is discussed in Chap. VI.

Automatic Start Motor.—An interesting variation of the ordinary form of polyphase induction motor uses a double winding on the rotor. A high-resistance squirrel-cage winding is supplied for starting. As the motor approaches running speed a centrifugal governor connects together the three terminals of a separate low-resistance phase winding similar to that of a wound-rotor motor. The motor then performs like a wound-rotor motor without external resistance. The principal feature of this motor lies in the fact that the primary may be connected directly across the line in starting. Good

starting torque is obtained with moderate current input and a simple switch suffices. The starting performance of a motor of this type is depicted in Fig. 211, Chap. XVI.

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CHAPTER VI

SPEED CONTROL OF POLYPHASE INDUCTION MOTORS

Methods of Speed Control.—The rate of rotation of an induction motor is determined by its synchronous speed and the rotor slip. In order to cause a change in speed, at least one of these factors must be varied. Several methods of speed control are applied to the polyphase induction motor. Three methods function through change of synchronous speed. These are:

Variable frequency system.
Multispeed motor.
Cascade set.

Three common control methods depend upon variation of the amount of slip. These are:

Secondary resistance or "rheostatic" control.
Primary voltage control.
Dynamic control.

Kramer system.
Scherbius system.
Frequency converter system.

Combinations of these methods are also used. The various systems have widely differing characteristics. Each finds application for particular classes of work. None of the methods is suited for universal usage.

VARIABLE FREQUENCY SYSTEM

Applicability.—The synchronous speed of an induction motor depends upon the circuit frequency and the number of poles per phase in the primary winding. The great majority

of induction motors operate on systems having a fixed frequency. The use of variable frequency or multiple frequencies involves special provision in the way of generators or frequency changers, complications which are not ordinarily justified. There are a few occasions, however, when such systems can be employed to advantage. It is therefore of interest to note briefly the qualifications of this method of speed control.

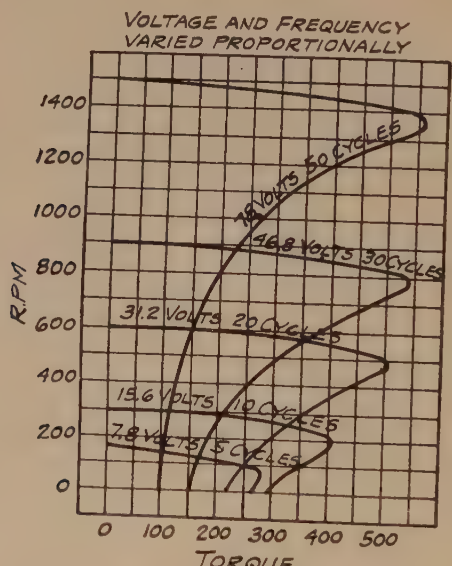
Characteristics.—If a motor be provided with a frequency below normal, it will operate at a correspondingly reduced speed. The voltage impressed must be reduced in the same proportion that the frequency is reduced. This is because the counter-voltage is proportional to the frequency, or rate of change of flux, and is thus also proportional to the speed. The effects of change of frequency and proportionate change of voltage practically offset each other in most respects so that the motor characteristics remain essentially unchanged, except in the matter of speed. The motor has approximately a constant current rating. It retains a constant torque capacity both as to normal and maximum values. The horsepower output is approximately proportional to the speed. The reduction in frequency is accompanied by diminishing core losses, tending to reduce heating. This tendency is about offset by the fact that reduction in speed lessens the ventilation so that the losses must be lower if the same operating temperature is to be maintained.

Where a wide speed range is involved, a limiting condition exists in that the primary resistance drop remains practically fixed while the impedance decreases with decreasing frequency. At very low speeds the resistance drop becomes relatively high and causes a diminution of pull-out torque.

Figure 43 shows the speed-torque curves of a 35 hp. squirrel-cage motor of special design, operated over a range of frequencies. It is to be noted that the pull-out torque falls off at decreased frequencies, particularly at very low speeds.

Another consideration of interest is shown in these curves. It may be noted that, at 50 cycles, the speed-torque curve is flat and the starting torque is low, the earmarks of a low-resistance squirrel-cage winding. At lower frequencies the

speed curve is less flat and the starting torque is higher, both relatively and actually. This is due to the fact that, at low frequencies, the secondary resistance, a constant quantity, achieves relatively greater influence and gives the motor the characteristics of a motor with high-resistance rotor. Incidentally it is evident that a squirrel-cage motor can be started to quite good advantage if connected to a generator whose speed and voltage are gradually increased.



(Courtesy, *Kilpatrick and Coleman, Electric Journal.*)

FIG. 43.—Speed-torque curves of a 35 hp. motor on various frequencies.

THE MULTISPEED MOTOR

Principles.—If an induction motor be operated on a circuit of fixed frequency, its synchronous speed can be changed only by changing the number of poles in the primary winding. This can be accomplished by using two or more separate primary windings, each having a different number of poles, or by using a single winding which can be connected so as to form different numbers of poles. Theoretically a number of speeds are possible. Practically, four synchronous speeds are the maximum

number feasible for squirrel-cage motors and two for wound-rotor motors. The squirrel-cage rotor is adapted to any number of poles whereas the secondary windings of the wound-rotor motor must be reconnected for different speeds.

Two synchronous speeds, bearing the ratio 2 to 1, may be secured by simple reconnection of one set of stator windings. A special winding is used with coils having a throw which is short pitch for the small number of poles and over pitch for the large number of poles. The high speed is obtained with the

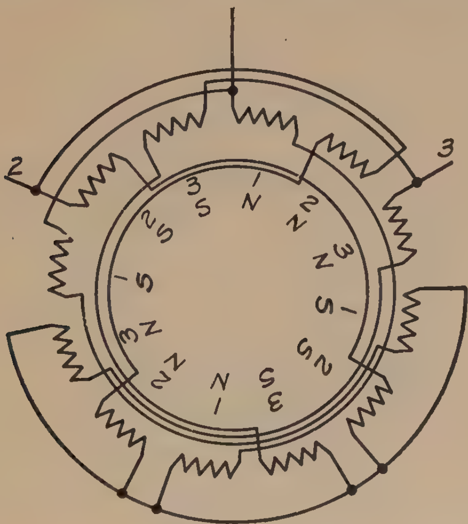


FIG. 44.—Multispeed motor stator winding connected four poles per phase, double star for high speed.

winding connected in a normal manner as shown in Fig. 44. Low speed is obtained by rearranging the circuits so that all coils of each phase have like polarity as indicated in Fig. 45. An equivalent number of consequent poles of opposite polarity then occur at intermediate points. The net result is twice the number of poles of half the arc. The speed of rotation of the field is then halved, reducing the synchronous speed accordingly. Figures 44 and 45 show how the coils of a four-pole motor may be reconnected to give eight poles. It will be noted that, in reconnecting, the coils have been changed from parallel

to series. When the rotation of the revolving field is halved, the rate of change of flux is proportionately decreased so that twice the turns are required in series, for the low speed, to produce the proper counter-voltage. The changes in the connections are made by bringing out the coil ends and completing the connections for either arrangement in the controller.

Speed ratios other than 2 to 1 must be obtained through the use of separate stator windings. Thus, a 60-cycle motor having a six-pole winding and a four-pole winding, will operate

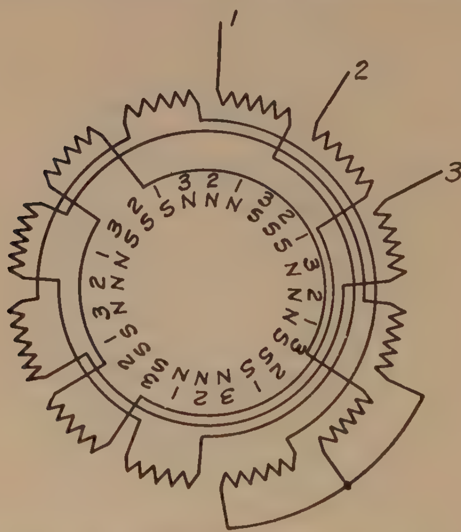


FIG. 45.—Multispeed motor stator winding connected single star for eight poles, giving half speed.

at either 1,200 r.p.m. or 1,800 r.p.m. If these two windings are arranged for reconnection for consequent poles, two additional speeds, 600 r.p.m. and 900 r.p.m. respectively, are possible. Where separate windings are employed, one set is placed in the bottom of deep stator slots, the second winding being inserted above them, there being thus two layers. Access to the lower coils for repairs can be gained only by removal of portions of the top layer.

External Connections.—The controller of a squirrel-cage motor having a two to one ratio is not complicated. But six

leads are brought out from a three-phase motor of this type. Two speeds from two separate windings also require six leads between motor and controller. Four speeds from two windings require twelve leads between motor and controller. Wound-rotor motors demand twice as many leads since their rotor windings ordinarily must be reconnected. This introduces complexity, requires more slip rings and brushes and makes the controller expensive. Wound-rotor motors are not regularly built for more than two synchronous speeds.

Multispeed motors are ordinarily built for three-phase circuits only. For use on two-phase circuits, Scott connected transformers are used to change to three phase. Controllers for two-phase motors would be more complicated and more expensive. It should be noted that changes from one speed to another are obtainable only by opening the primary circuit and then closing it with different connections. This necessary interruption of the power supply is an undesirable feature of the multispeed motor.

Performance.—The multispeed motor is not in reality an adjustable speed machine since a limited number of speeds can be obtained. In the great majority of applications but two speeds are possible. At each setting the motor operates essentially as a simple induction motor, having squirrel-cage constant speed or wound-rotor varying speed characteristics, according to type. Since most multispeed motors are of the squirrel-cage design they offer two, three or four widely differing but approximately constant speeds. The torque remains approximately the same for each connection and the horsepower capacity is greater at the higher speeds. A multispeed motor is essentially a constant torque machine.

The efficiency of multispeed motors is quite high, being but slightly inferior to that of the simple induction motor. The efficiency is usually a little better at the faster speed. The power factor of the multispeed motor is likely to be rather low, particularly at the lower speeds. The deep slots required to carry the double windings contribute to this fault. The starting torque per ampere varies approximately inversely as the speed, depending upon the connection used at starting. Squirrel-cage multispeed motors require a compensator for

starting. Change from one speed to another can usually be accomplished by movement of the drum controller which reconnects the windings. This change is accompanied by a sudden rush of current similar to that at starting. Figure 46 shows the characteristics of a two to one, squirrel-cage multi-speed motor.

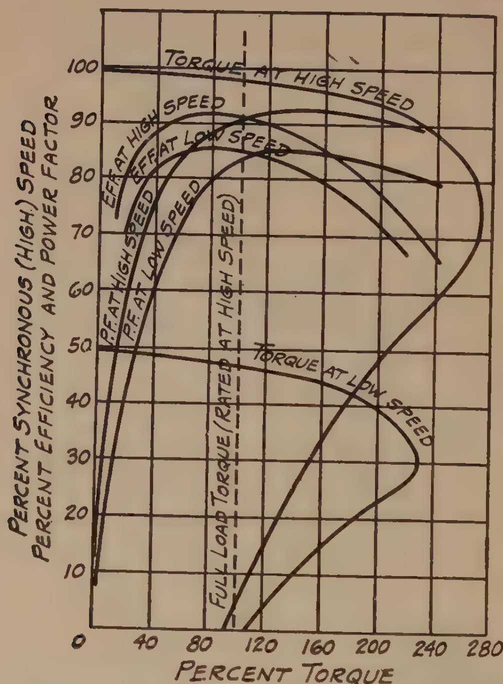


FIG. 46.—Characteristics of a multispeed induction motor having 2 to 1 speed ratio.

Applicability.—Multispeed motors find a limited field of application. Where two or three fixed speeds will suffice and constant torque is required, they are well adapted and inexpensive. The great majority of these motors have squirrel-cage rotors. Multispeed motors with phase-wound rotors have been used to a limited extent for main roll drives in steel mills and elsewhere. The multispeed motor has been recently adopted for elevator service and similar duty, the fast speed

being the normal running condition, the slow speed being used as a slow-down in approaching a stop.

CASCADE SETS

Principles.—By means of cascade connection, two induction motors that are rigidly connected, usually upon the same shaft, may afford a number of synchronous speeds. A combination of two such motors is called a cascade set. One of the motors must have a wound rotor. The two motors are usually arranged for different numbers of poles. By operating either motor alone, two synchronous speeds are obtainable. If the motors are built for multi-speed connections of the stator windings four synchronous speeds are possible through use of the motors individually. If the secondary of the wound-rotor motor be connected to the primary of the second motor as in Fig. 47, the second motor is subjected to a voltage at variable frequency. The set will operate at a point dependent upon the combined number of poles of the two motors. This may be seen most readily by considering a cascade set composed of two motors, both having the same number of poles. When the first motor is at rest, its rotor winding has generated within it a voltage at line frequency and this is applied to the stator of the second motor. Both motors then tend to accelerate. As the speed increases, the frequency of the current in the circuit composed of the rotor of the first motor and the stator of the second motor, is decreased. At half speed the fre-

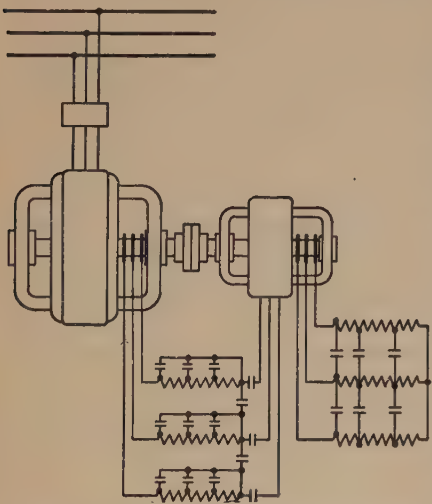


FIG. 47.—Connections of two motors in cascade.

quency of the current in this circuit is half line frequency. At this frequency the second motor will run at half speed. If the rotor of the first motor should increase its speed further the frequency applied to the stator of the second motor would decrease and the second motor would tend to slow down. It is thus evident that the normal speed of the set is half that of either motor operating alone. In general, the speed of a cascade set equals:

$$\frac{\text{cycles} \times 120}{P_1 \pm P_2},$$

where P_1 and P_2 are the number of poles of the first and second motors, respectively. The plus sign is used in the case of direct cascade connection and the minus sign in the case of differential cascade connection. Motors are connected in direct cascade if they both tend to start in the same direction and in differential cascade if they tend to start in opposite directions. It should be evident that direct cascade reduces the speed of a set below that of the synchronous speed of the first motor while differential cascade increases the operating speed above the synchronous speed of the first motor. If a set is arranged for both direct and differential cascade connection the speed range may be materially increased. The change from one type to the other is accomplished by reversal of one phase in the secondary circuit of the first motor.

The differential cascade connection is limited in its application. A differential cascade set exerts comparatively low starting torque since the motors are opposing each other. It is necessary to bring the set up to speed by use of the second motor alone. Differential operation may then be secured by reduction from the higher speed, using the cascade connection. It is necessary that the second motor have fewer poles than the first motor in order that this higher speed may be possible. A differential cascade set will not accelerate from a low speed.

Performance.—It will be seen that cascade sets are similar to multispeed motors in that they afford a number of fixed synchronous speeds. If the second motor of the set is of the wound-rotor type it is possible to utilize rheostatic control to obtain intermediate speeds. The number of synchronous

speeds available from direct cascade sets together with the number of terminals to be brought out to controllers is given in the following table:

First motor	Second motor	Number of sync. speeds	Number of leads
Wound-rotor	Squirrel-cage	3	9
Wound-rotor	Wound-rotor	3	12
Wound-rotor	Squirrel-cage multispeed	5	12

The capacity of a cascade set depends upon the relative sizes of the units and the method of operation and much depends upon the behavior of the load at different speeds. The torque of each motor of the set is approximately equal to the total torque × the ratio of the number of poles of that motor to the number of poles of the two motors combined. Thus, in a set having one unit with four poles and one unit with eight poles, the four-pole motor will exert one-third of the combined torque. Since the power of the four-pole motor must pass through the eight-pole motor, it does not increase the maximum torque of the set. As the set operates in cascade at reduced speed the capacity is proportionately reduced, The breakdown output of the set will be a little less than two-thirds of that of the large motor running alone. The lowering of the breakdown capacity through cascade operation forces the use of comparatively large units. With two units having equal numbers of poles the breakdown capacity of the set in cascade is less than half that of a single unit. If one machine has sixteen poles and the other four poles the breakdown capacity is nearly four-fifths of that of the larger sixteen-pole motor. Loss of overload capacity is thus less severe where moderate speed changes are secured by addition of a small motor having few poles in cascade with a larger motor with a comparatively large number of poles. With differential cascade connection the torque of the second motor opposes that of the first motor and thus reduces the torque of the set with increase of speed. The proper application of a cascade set thus requires accurate knowledge of load conditions.

A number of speed changes may be accomplished with cascade sets without opening the primary circuit. This is done by introducing resistors and cutting them out in steps. Figure 47 shows the location of the resistors used for this

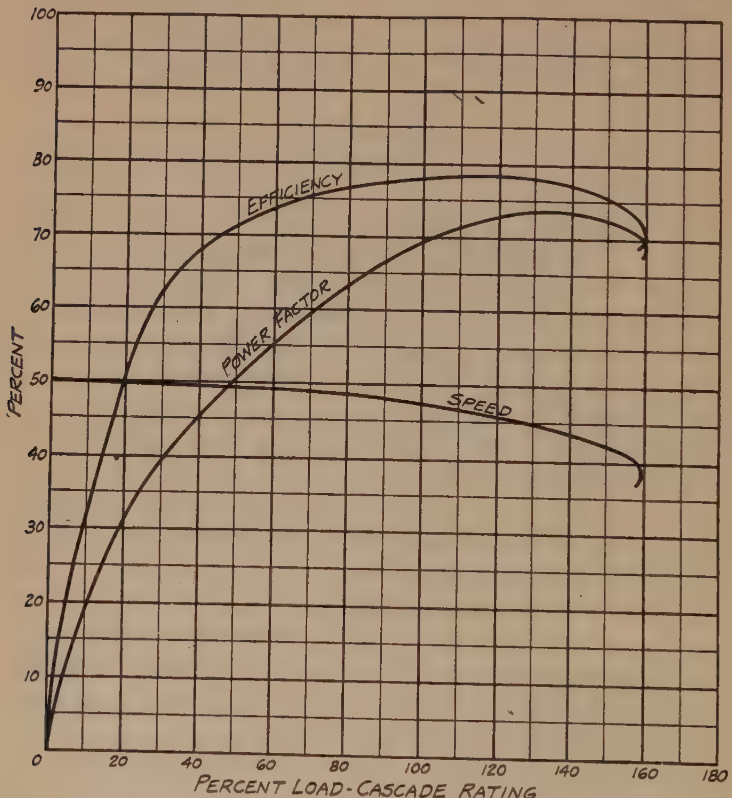


FIG. 48.—Characteristics of a cascade set comprising two duplicate units.

purpose. The ability to change speed without primary switching is desirable.

The efficiencies of the individual units of a cascade set are the same as those of ordinary induction motors of the same type. The efficiency of the combined set is somewhat less than that of a multispeed motor of similar capacity. The efficiency is necessarily low since the input of the second unit must pass

through the first unit. The power factor of a cascade set is rather poor. The magnetizing current for the set is that of the combined units and the magnetic leakages are also additive. Large magnetic leakage causes not only poor power factor but also low maximum torque. Figure 48 shows the characteristics of a set made up of two like units operating in cascade.

Applicability.—Cascade sets are not commonly employed in small sizes but large units are sometimes used where special speed ratios other than two to one are desired. They may also be used where high primary voltage would prohibit the switching operations incident to the use of the multispeed motor. It is desirable that the horsepower required at high speed be greater than that at low speed since the capacity of the set is decreased at low speeds. Cascade sets are comparatively less expensive, more economical and more efficient where only moderate changes are obtained through the use of a comparatively small second motor.

SECONDARY RESISTANCE OR RHEOSTATIC CONTROL

Principle.—It has been already pointed out that the actual speed of an induction motor is somewhat below synchronous speed. The amount of difference between synchronous speed and actual speed depends upon the slip. The slip depends upon the load and the resistance of the rotor circuit. Evidently, with a given load, it is possible to secure a moderate change in speed through variation of the slip by changing the resistance of the secondary circuit. This method is applicable by means of wound-rotor motors supplied with controllers and external secondary resistors.

Performance.—This is a rather commonly used method but is limited in desirable features. But a moderate range of speeds is possible. Synchronous speed is the maximum rate obtainable and about half synchronous speed is the lowest value feasible in the majority of cases. The speed cannot be termed adjustable since it is adjustable only at constant torque. Any change of load causes a change in speed, since, as before stated, the slip depends upon both load and secondary resistance. It is evident that a varying load will give a varying

speed. Reduction of load causes increase of speed. With very light loads the slip is greatly reduced and the speed reaches nearly synchronous value. At light loads it is impossible to secure more than a 5 to 10 per cent range of speed control without the use of extremely large resistance. A given setting of the controller will provide a 10 per cent slip at light load and a 50 per cent slip at full load. The speed at any controller position is thus indeterminate and depends entirely upon the load. The method is thus ill adapted to changeable loads except in connection with continuous manual attention. Since the speed of a motor varies widely with load changes, it is necessary that the exact amount of load be known if a definite load speed is to be obtained. Overmotoring is not permissible if a definite reduction is desired since the range of obtainable speeds is less, the smaller the load. The characteristics of rheostatic control are well illustrated by the curves in Fig. 34, Chap. V, showing the operation of the wound-rotor motor with different values of secondary resistance.

Efficiency.—Since the primary magnetism of the motor remains practically constant, a given torque requires approximately the same secondary current at different speeds obtained through change of rotor resistance. A motor of this type is a constant torque proposition and its horsepower output capacity is reduced at decreased speeds. At full speed, full load, most of the input is converted to mechanical output. At half speed the same input develops but half the mechanical output. The balance of the power is wasted in the secondary resistors. The speed reduction is obtained through heavy sacrifice in efficiency. In general, the efficiency is reduced almost in direct proportion to the reduction in speed. The low efficiency makes this method of speed control ill suited for motors of moderate or large size operating rather continuously at reduced speeds under load. The wastage of power in such cases may be enormous.

Where it is desired to find the efficiency of a wound-rotor motor at any given speed, the following method may be applied. On a speed efficiency curve, plot known value of efficiency at full-load torque and full-load speed. Connect this point with the zero of coordinates. The efficiency with full-load torque at

any reduced speeds may then be read directly from this curve. If the half-load maximum speed efficiency is known, a similar line may be drawn to represent the efficiency with this torque at different speeds.

Power Factor.—The power factor of the wound-rotor motor with rheostatic control is dependent upon the torque, irrespective of the speed, and is rather high, being better at full load than at fractional loads.

Controller.—The same secondary controller is used both for starting and for speed control. Resistors for speed-control service must be different from those designed for starting duty only, as they must have greater heat-dissipating ability because of the more continuous service. In other respects the controller as used for speed control is identical with that used for frequent starting and other services.

Applicability.—Rheostatic control is often satisfactory for work requiring a low speed for setting up and a higher speed for operating. The low efficiency at reduced speed is here unimportant. It is adapted for use where a limited speed range is desired and where the load is not of a fluctuating character. It is also applicable for intermittent service with continuous manual control. There are many uses for this method of speed control but there are likewise many kinds of service where it is not satisfactory. A few typical cases may be mentioned. Rheostatic control is not suited for machine tool drives since the speed range is too limited and the rotation altogether too unsteady. It is not suited to any work requiring fairly constant speed with varying loads. It is not well suited for work requiring full horsepower at reduced speeds. It is undesirable for continuous service at greatly reduced speeds because of its low efficiency.

PRIMARY VOLTAGE CONTROL

Methods.—The slip of an induction motor with squirrel-cage rotor may be varied by changing the voltage applied to the primary windings. The slip, at a given torque, varies approximately inversely as the square of the applied voltage. The line voltage may be reduced, to lower the speed, either by

means of an auto-transformer with taps, affording adjustable voltage, or by the insertion of resistance in the primary circuit. The two methods afford slightly differing characteristics.

Performance.—The torque capacity of an induction motor varies as the square of the applied voltage. A reduction in applied voltage brings about a marked decrease in available torque. At half voltage, the maximum torque is but a quarter of its normal value. The possible range of speed variation is limited by the accompanying reduction in pull-out torque.

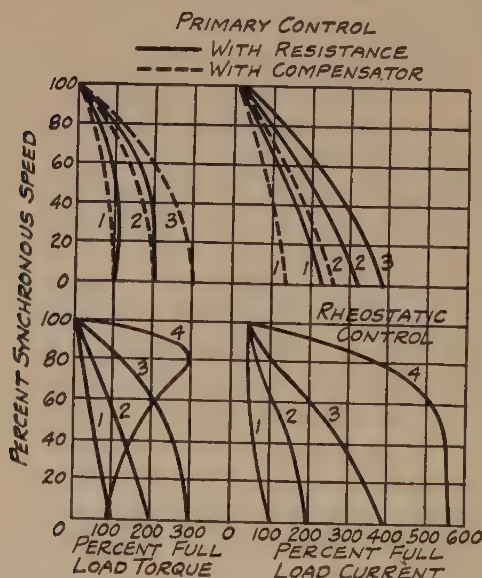


FIG. 49.—Comparison of primary voltage and rheostatic control methods.

It has been pointed out on previous pages that an induction motor with high-resistance rotor exerts a better torque with reduced primary voltage than a motor with low-resistance rotor. It also affords better starting torque per ampere. For these reasons, motors for primary control are specially designed having low magnetic leakage and high-resistance squirrel-cage rotors. The large rotor loss incident to this design makes necessary the use of comparatively large, easily rated frames which are consequently expensive. Auto-transformer control

is more complicated and costly than series-resistance control and the auto-transformer connections must be switched off and on and cannot be short-circuited as with resistance control. Auto-transformer control affords a higher efficiency than resistance control and takes less current but gives a poorer power factor.

The comparative characteristics of rheostatic control and primary control with auto-transformers and resistors may be studied from Fig. 49. The figure shows typical speed-torque and speed-current curves for the three methods. Curve 1 gives full-load torque at starting. With rheostatic control 100 per cent full-load current is taken, with auto-transformer control the current is 140 per cent and with series-resistance control it is 225 per cent. For starting, it is evident that rheostatic control affords much better torque per ampere. Curve 3 shows the same torque per ampere for all three methods of control. This is because full primary voltage is impressed in all cases and the secondary resistance on this controller point with rheostatic control is equal to that of the high-resistance squirrel-cage rotor.

Applicability.—The advantages of primary control are the use of the squirrel-cage motor with no secondary leads and the simplicity of the primary resistance controller. The disadvantages are: poor speed regulation, low efficiency, a large and consequently expensive motor, small range of possible speeds and rapid reduction in torque at decreased speed. Primary control is used in powder mills and for such cases where explosion or fire might result from a spark at the slip-rings of a wound-rotor motor. Other applications of primary control are for trolley and traverse motors or cranes, due to the lesser wiring; on some elevators and as starting motors for large rotary converters or synchronous motors where the efficiency is of minor importance and simplicity is paramount.

DYNAMIC CONTROL

Principles.—The torque of an induction motor is developed by current in the rotor conductors reacting upon the primary magnetism. The primary magnetism of an induction motor

remains practically constant. In order to develop various values of torque as demanded by an external load, the rotor current must vary. This is brought about in the ordinary motor by small changes in the slip such that the voltage generated in the rotor circuit is varied and the current automatically adjusted to the load. The rotor circuit, then, has a generated voltage overcoming the rotor resistance.* Let us consider what will occur if, in addition to the rotor resistance, a counter-voltage is introduced into the rotor, the value of this counter-voltage being adjustable. A given torque still requires a given current and sufficient margin must exist between generated voltage and counter-voltage to force the required current through the secondary circuit resistance. The greater the counter-voltage the greater the generated voltage required, hence the greater the rotor slip. It is thus seen that it is possible to vary the speed of an induction motor materially by introducing a counter-voltage into the secondary circuit. Since the frequency of the secondary circuit is variable, dependent upon the slip, it follows that the frequency of the counter-voltage must vary in like manner.

Methods.—Dynamic control is a name given to all the methods of induction motor speed control involving the use of auxiliary machines arranged to introduce a counter-voltage into the secondary circuit and to transfer the secondary or slip energy of the main, wound-rotor motor back to the source of supply or to convert it to mechanical power and apply it to the shaft of the main motor. There are several methods in use. These may be classified according to the auxiliary equipment required as follows:

Rotary converter or Kramer system.
A.C. commutator motor or Scherbius system.
Frequency converter system.

THE KRAMER SYSTEM

Constant Torque System.—The Kramer system employs a rotary converter to convert the slip energy of the main motor to direct current. This is then used in a direct-current motor.

* Revolving field theory.

This motor may be part of a motor generator set or it may be attached to and made a part of the main induction-motor drive. The layout and main connections for the rotary-converter motor-generator system are shown in Fig. 50. The operation is as follows: At starting, the main motor is operated alone with the transfer switch thrown to connect the external re-

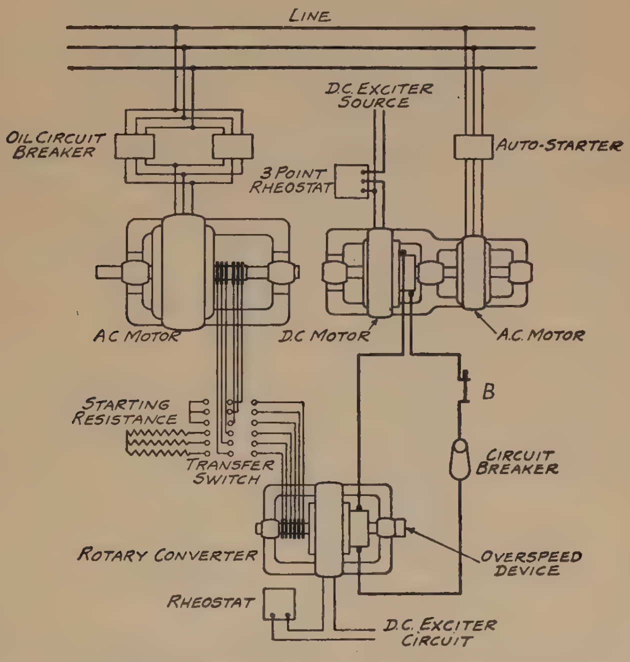


FIG. 50.—Principal connections for Kramer system with motor-generator set.

sistors in the secondary circuit and the motor is accelerated in the usual manner by cutting down the secondary resistance. To place the auxiliary apparatus in service, the induction motor of the motor-generator set is started. The field of the direct-current unit is reduced to zero so that the set merely runs light from the alternating-current side. Normal field current, obtained from an exciter, is placed upon the converter, which is at rest. The direct-current side of the converter is then connected to the direct-current unit of the motor-generator set

by closing switch B. While the main motor is running light at full speed with small slip, the transfer switch is thrown over to disconnect the resistors and substitute therefor the alternating-current side of the converter. The converter starts to rotate very slowly since it runs in synchronism with the slip of the main motor. This completes all circuits and places the system in readiness for speed adjustment.

Principles of Action.—If the field of the direct-current unit be strengthened, it will generate a voltage which is impressed upon the direct-current end of the converter. This increases the voltage at the alternating-current end of the converter and introduces a counter-voltage into the secondary circuit of the main motor, slowing it down. This increases the slip frequency and causes the converter to increase its speed but it does not affect the voltage ratio of the converter. The stronger the excitation of the direct-current unit, the greater the counter-voltage introduced into the secondary circuit of the main motor. By adjustment of the field rheostat of the direct-current unit it is possible to adjust the speed of the main motor for any desired rate below synchronism. With a given rheostat setting the speed of the main motor remains nearly constant, affording characteristics similar to those of an adjustable speed direct-current shunt motor.

This scheme can also be used to increase the speed of the main motor above synchronism. As the field of the direct-current unit is weakened the speed of the main motor rises. If the field of the direct-current unit be reversed, the direction of rotation of the converter is reversed. The voltage applied to the secondary of the main motor is also reversed so that, instead of being a counter-voltage opposing the flow of rotor current, it aids the flow. It is no longer necessary for the rotor to slip below synchronous speed to generate a voltage to set up the flow of rotor current. The rotor therefore speeds up above synchronism. In doing so it cuts the magnetism of the stator's revolving field in a sense opposite to that existing below synchronism and thus generates a counter-voltage. The more the field of the direct-current unit is strengthened the greater the voltage impressed at the slip rings encouraging the flow of rotor current. The higher, then, the speed must

be in order that a counter-voltage may be generated sufficient to hold down the rotor current to the value demanded by the torque of the external load.

The operation may be viewed in another manner if it is considered that, at speeds below synchronism, the frequency of the converter is subtracted from that of the main motor, resulting in a slip of the rotor below synchronism. Above synchronism the converter reverses its phase relations and causes the slip to become negative, so that the speed increases. There is a small range of speed very close to the synchronous value at which the rotary converter stands still and the main motor operates as a simple wound-rotor motor with secondary resistance corresponding to that of the secondary circuit through the converter and intermediate connections. This occurs while the voltage of the direct-current unit is *nil*. While the converter is at rest and when the direct voltage is being built up in either direction, direct current is delivered to the slip rings of the main motor since the converter does not convert while at rest. At this instant the main motor acts as a synchronous motor and comes up to exact synchronism.

Over a range of about 4 per cent above and below synchronism the operation of the set is unstable and the torque developed is but a fraction of full-load value.

We have considered the relations of the voltages and the currents in the various circuits but have not studied the interchanges of power between the various machines. When the main motor is running below synchronism the rotor currents flow in opposition to the counter-voltage impressed from the converter. They therefore represent negative power input, or power output. Slip energy, wasted in resistors with rheostatic control, is thus transferred to the converter. It is here changed to direct current and transmitted to the direct-current unit which converts it to mechanical power. The speed of the motor-generator set is thus raised so that the alternating-current unit operates above synchronism (if of the induction type) and delivers energy to the supply circuit. The slip energy of the main motor is partially wasted in the losses of its secondary circuit but most of it passes through the auxiliary machines and is returned to the supply lines.

Performance.—When the set is operating above synchronism the alternating-current unit of the motor-generator set operates as a motor. The direct-current unit runs as a generator and delivers, through the converter, the energy which enables the main motor to run above synchronism. The proportion of the energy supplied through the auxiliary equipment depends upon the margin of operating speed above synchronous speed. The amount of energy received by the auxiliary equipment from the main motor operating below synchronism, depends upon the slip.

It will be seen that this system is a constant torque proposition. Below synchronous speed a given input to the main motor is partially converted to mechanical power and partially returned to the supply lines. At approximately synchronous speed, most of the input is converted to mechanical power, the losses alone being deducted. Above synchronous speed the auxiliary equipment aids indirectly in driving the main motor shaft. The mechanical horsepower output thus varies approximately directly with the speed.

Apparatus Required.—The apparatus used for a dynamic control installation as above described is practically all standard equipment. The main motor is of the ordinary wound-rotor type. It is possible to furnish auxiliary equipment to provide dynamic control for any ordinary wound-rotor motor. The rotary-converter is commonly a standard machine wound with the same number of phases as the secondary of the main motor. It is usually advisable, particularly in the larger sizes, to have the main motor rotor wound six phase with six slip-rings. This gives a more economical converter design and better distributes the heating in the converter armature. The frequency and voltage rating must be consistent with the values obtained from the secondary of the main motor under operating conditions. A 25-cycle converter will often apply for use in connection with a 60-cycle main motor. The capacity of the converter is determined by the secondary current rating, which is the same at all speeds. The size of the motor-generator set depends on the speed range desired. For a range of speed 30 per cent above and below synchronism the horsepower capacity of the motor-generator will be about 30 per cent of that of the main

motor. Since this set may operate at any rotation, a high speed is used to reduce its cost. The direct-current unit is an ordinary direct-current motor. Its shunt field is separately excited from the same circuit as that exciting the converter. In some cases it is found desirable to furnish a compound winding for the direct-current unit. Increase of load on the main motor increases the load on the auxiliary equipment. This increase causes a strengthening of the series field excitation of the direct-current unit and causes the main motor to slow down. The speed regulation of the main motor may be varied by adjusting the series field of the direct-current unit. The alternating-current unit of the motor-generator set may be either a synchronous or an induction motor. The induction machine is simpler and is commonly used.

Constant Horsepower System.—The rotary-converter direct-current-motor type of dynamic control is similar to the previously explained system with the exception that the motor-generator set, returning slip energy to the supply system, is replaced by a direct-current motor mounted on the common shaft with the main motor. Figure 51 shows the layout and main connections of this system. The direct-current motor converts the slip energy into mechanical power at the main shaft. The operation and speed adjustment are similar to those of the converter-motor-generator system. To obtain a drooping speed characteristic the direct-current motor must be equipped with a comparatively strong series field. In the motor-generator system the speed of the direct-current unit was approximately constant. In this second system the direct-current motor speed drops as the main motor slows down. In order to maintain the counter-voltage at the slip rings the excitation of the direct-current machine must be correspondingly increased. It will be seen that this system of dynamic control is essentially a constant horsepower proposition. The total input, minus the losses, is converted into mechanical power at the main shaft. Near synchronous speed the main motor delivers most of its input at the shaft. At reduced speeds the direct-current motor adds its torque to that of the main motor. At speeds above synchronism the torque of the direct-current unit opposes that of the main motor. The net

torque thus varies with the speed, giving a constant horsepower characteristic.

The direct-current motor system of dynamic control is, in general, more costly than the motor-generator system. The main motor is usually a large, slow-speed machine. Since the direct-current motor is preferably mounted on a common

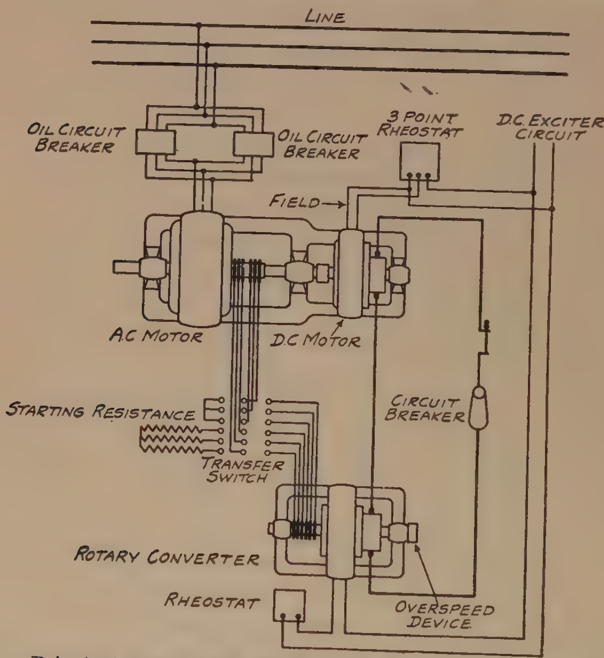


FIG. 51.—Principal connections for Kramer system with auxiliary direct-current motor.

shaft with the main motor, it runs at comparatively low speed and is therefore large for its rated output. The relative capacity of the direct-current machine depends, as in the previous system, upon the speed range to be covered. This machine must handle its maximum output at its minimum speed, however, thus requiring a relatively larger frame. It is of particular advantage with this type of set that the main motor speed be as high as feasible since the cost of the auxiliary direct-current motor is so largely affected, as well as that of the main motor.

Applicability.—The Kramer system is particularly adapted for use on 60-cycle circuits where a standard 25-cycle converter can be utilized. It enjoys some special advantages for wide speed ranges. It is generally used for the larger installations involving auxiliary equipment of 1,000 hp. capacity and upwards. The fact that standard apparatus is employed and simple connections used, is a favorable factor. The constant

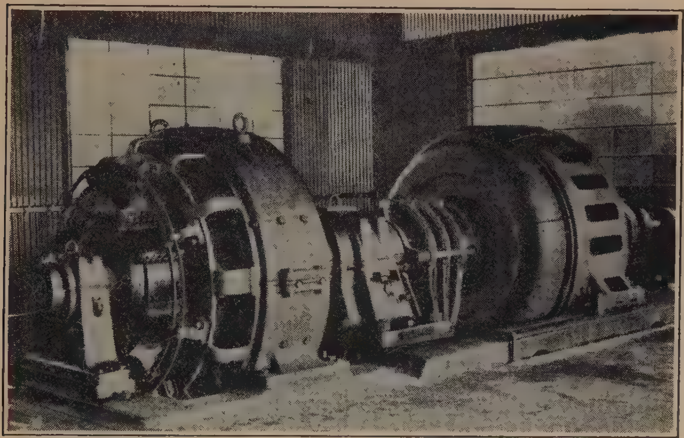


FIG. 52.—Main wound-rotor induction motor and auxiliary direct-current motor for constant horse power Kramer set.

horsepower type of drive is of advantage where the load is such as to involve heavier torques at low than at high speed.

THE SCHERBIUS SYSTEM

Description.—The Scherbius system of induction motor speed control resembles the Kramer system in that it functions by introducing into the secondary circuit of a main wound-rotor motor a counter-voltage which is subject to adjustment. The auxiliary equipment used to supply this counter-voltage comprises mainly a so-called three-phase compensated commutator motor which is in many respects similar to a direct-current motor. This commutator motor is mounted on a common shaft with a squirrel-cage induction motor of perhaps 25 per cent of the capacity of the main motor. The size of this set

is determined by the speed range and the horsepower output at maximum departure from synchronism. Figure 53 illustrates a regulating set of this type.

There are several types of three-phase regulating motors, depending upon the characteristics desired. The type most commonly used in the "Double Range Scherbius System" will be briefly described and the functioning of the system outlined.

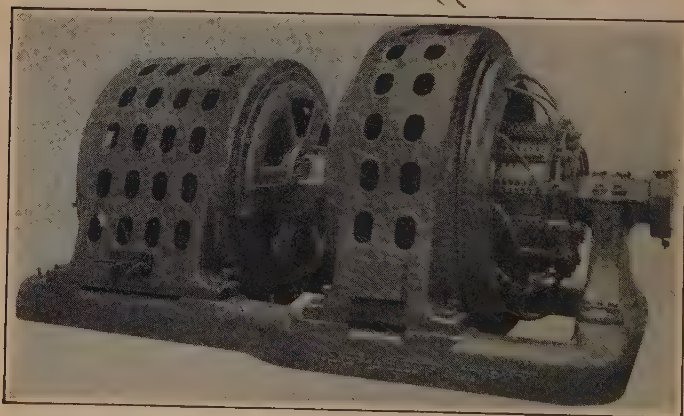


FIG. 53.—Regulating set for Scherbius system comprising three-phase commutator motor and induction unit.

Principles of Action.—There is shown in Fig. 54 a simplified diagram of connections of a double range Scherbius set. Here it will be noted that the slip-rings of the main motor are connected to the brushes of the commutator motor. This commutator motor must evidently develop a voltage having the same frequency as the secondary voltage of the main motor. This is the case. The stator of the commutator motor carries field windings F_1, F_2, F_3. These fields are excited by current at slip frequency. The armature of the commutator motor is driven at practically constant speed by the induction motor on the common shaft. Thus the voltage generated in the commutator motor and taken off at its brushes is of frequency determined by the field excitation, that is, slip frequency. If the slip of the main motor increases or decreases, the frequency

of the commutator motor automatically adapts itself to the changed condition.

Since the rotation of the armature of the commutator motor is constant, the voltage generated is proportional to the flux set up by the fields F_1, F_2, F_3. (The fields C_1, C_2, C_3 are com-

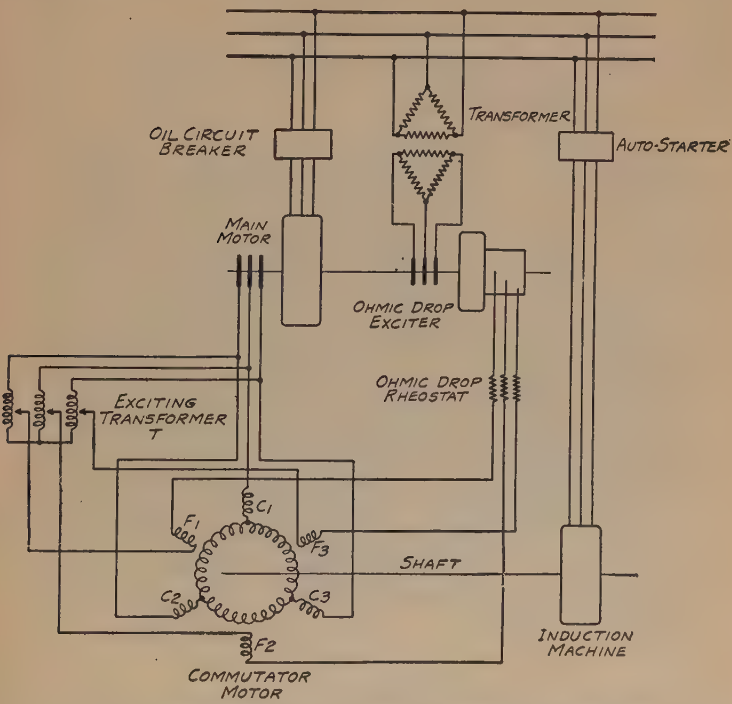


FIG. 54.—Simplified diagram of connections of double range Scherbius set.

pensating windings.) The flux set up in fields F_1, F_2, F_3 is proportional to the current passed through these windings. It will be noted that these fields are excited, in part, from a transformer which is subjected to the secondary voltage of the main motor. Thus, as the slip and secondary voltage of the main motor increase, the voltage impressed on field windings F_1, F_2, F_3 increases directly. This would apparently tend to increase the strength of these fields. This tendency

is offset however by the counter-voltage induced in these fields due to the fact that their flux is alternating. This counter-voltage is proportional to the field flux and also to the field frequency (slip frequency). Any increase in slip thus increases the counter-voltage in the field windings and maintains the field current and flux at a fixed value. Thus, the commutator motor tends to generate at its brushes, a constant voltage at slip frequency. This voltage impressed at the slip rings of the main motor simply requires that motor to develop an excess of slip voltage sufficient to overcome this opposition in addition to the resistance drop due to secondary load current.

To change the speed of the main motor, the armature voltage of the commutator motor must be changed. This can be done by changing the strength of the fields F_1, F_2, F_3. This is done by increasing the voltage impressed on these windings by connecting these windings to different taps of the transformer T. For each tap point there will result a definite field strength which will cause the commutator motor to develop a definite voltage in opposition to the slip voltage of the main motor, thus adjusting the speed of the latter.

When the main motor is operating near synchronous speed, its secondary voltage is very small, hence the voltage across transformer T is small and the excitation of fields F_1, F_2, F_3 approaches zero. A motor functioning purely as above described evidently could not operate at synchronous speed.

Ohmic Drop Exciter.—In order that the Scherbius set may be made to operate through synchronous speed, an additional unit, called an "ohmic drop exciter," is provided. This is in reality a small frequency converter. It is shown in Fig. 55 and is mounted on the shaft of the main motor so that its speed is always the same as that of the main motor.

This machine has an armature like that of a rotary converter, having both commutator and slip-rings. The field punchings which encircle the armature are without windings. The commutator is provided with brushes in multiples of three in order to deliver three-phase current. The slip-rings are connected through a transformer to the main power lines. If voltage be applied to these slip rings while the armature is at rest, the alternating currents in the various coils produce a

magnetic field which revolves around the rotor at a speed depending upon the impressed frequency and inversely upon the number of poles in the armature winding, just as in the ordinary induction motor. If the armature be rotated at synchronous speed in a direction opposite to the phase rotation of the revolving field, the resultant magnetic field does not actually rotate but stands still in space. The armature conductors, revolving at synchronous speed, cut this stationary flux and have generated in them a voltage which causes the

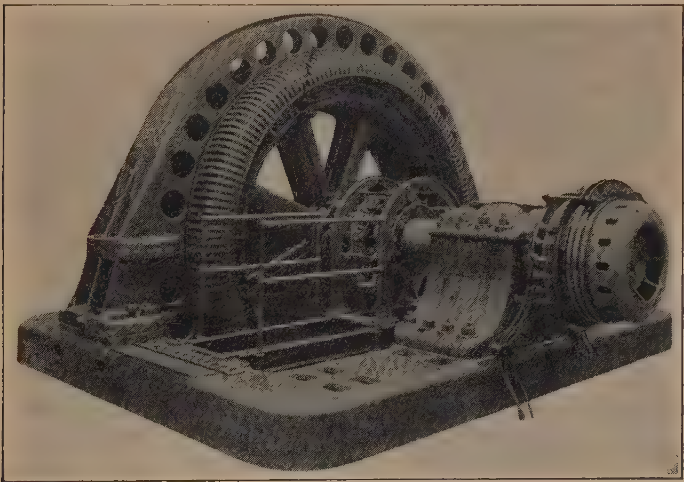


FIG. 55.—Main motor and ohmic-drop exciter, Scherbius system.

delivery of direct current at the brushes, just as in a direct-current generator. The voltage delivered at the brushes is proportionate to that impressed at the slip rings, just as in a rotary converter.

If the armature of the ohmic drop exciter be rotated in the same direction as before, but at a lesser speed, say two-thirds synchronous speed, then the resultant field is not stationary. The armature is rotated forward at two-thirds synchronous speed. The revolving field produced by the armature rotates backward at synchronous speed. The resultant field then rotates backward at one-third synchronous speed. The voltage appearing at the stationary brushes is thus alternating

and its frequency is one-third that of the circuit impressed at the slip rings. The voltage delivered at the brushes maintains a fixed ratio to that impressed at the slip rings and is thus constant, regardless of the speed. This will be evident if it is considered that the field, which is set up by the armature, always rotates at the same speed with respect to the armature. The armature conductors thus cut the same flux and have generated in them the same voltage regardless of the rate of mechanical rotation.

If the armature of the ohmic drop exciter be rotated in the same direction as before, namely, opposite to the field rotation, and if the speed of rotation be greater than synchronous speed, then the resultant field will rotate in space in the same direction as the mechanical rotation and at a speed proportional to the marginal speed above synchronism. The voltage generated in the armature will have a phase rotation reverse to that when operating below synchronism.

To summarize, the ohmic drop exciter produces voltage of constant value, at slip frequency, and whose phase rotation changes as the speed of the exciter passes through synchronous speed, at which point direct current is produced.

Returning to the diagram in Fig. 54, we note that the ohmic drop exciter is so connected that it can supply exciting current to the fields F_1, F_2, F_3. It is utilized for this purpose. Resistance is inserted in the circuit and this is so manipulated that the resistance drop in the fields plus the rheostat is always equal to the voltage generated by the exciter. The exciter is thus made to supply just enough excitation voltage at the fields to overcome the resistance drop in the latter at all times and with differing values of field current.

Operation below and above Synchronism.—When the main motor is operating at a speed wide from synchronism, that is, with large slip, the counter-voltage across the field-windings F_1, F_2, F_3, is nearly all induced voltage and the resistance drop is relatively small so that the ohmic drop exciter has little influence. As the speed of the main motor approaches synchronism, the induced voltage across F_1, F_2, F_3, is reduced and the resistance drop becomes proportionately greater.

At synchronous speed the ohmic drop exciter produces

direct-current which, flowing in fields F_1, F_2, F_3, sets up a fixed field and causes a direct-voltage to be generated in the armature of the commutator motor. As a result of this voltage, direct-current flows in the secondary of the main motor and enables this unit to develop torque. Due to the slight droop in speed under load it is necessary, in order to attain synchronism, first to diminish the excitation of fields F_1, F_2, F_3, and then apply reversed excitation. An increase in field strength of F_1, F_2, F_3, then causes the voltage of the latter to increase, causing an increased current flow through the rotor of the main motor, increasing the torque of the latter and causing it to increase its speed above synchronism. The set then operates in a manner similar to its operation below synchronism except that the phase rotation of the main motor secondary, the ohmic drop exciter, the fields F_1, F_2, F_3, and the commutator motor are all automatically reversed.

When operating below synchronism the polyphase commutator motor receives slip energy from the main motor secondary. It drives the induction unit of its set at a speed slightly above synchronism, causing the latter to function as an induction generator delivering electrical energy to the main supply system. Thus the slip energy of the main motor, less the losses in the auxiliary machines, is returned to the power system.

When operating above synchronism conditions are reversed. The induction unit of the auxiliary set acts as a motor, taking electric power from the supply system and driving the polyphase commutator motor. The latter delivers electric energy to the secondary of the main motor, which converts it into mechanical power.

Power Factor.—Several means are commercially employed to maintain a good power factor for the set. Power factor may be improved by certain adjustments of the exciting transformer which changes the phase of the exciting current. Adjustment of the voltage of the ohmic drop exciter and ohmic drop rheostat, in conjunction with the above, permits adjusting the power factor at various speeds. An out-of-phase component of exciting current may be obtained at speeds near synchronism by means of taps to the fields of the regulating motor from the

ohmic drop exciter. By these means a power factor of 95 per cent or better may be maintained over a range of speeds and loads.

Performance.—The Scherbius system is essentially a constant torque equipment. At reduced speeds the slip energy is deducted from main motor input and returned to the power system. At speeds above synchronism electrical power is introduced into both stator and rotor of the main motor, increasing its horsepower capacity. A constant horsepower drive may be obtained by mounting the commutator motor on the common shaft with the main motor, but this is not ordinarily commercially feasible.

The double-range Scherbius system enjoys an advantage in that the synchronous speed is intermediate in the operating range. The size of the auxiliary set is determined largely by the amount of slip energy handled which, in turn, depends upon the slip. Thus with a double-range equipment the auxiliary set is only about half the size necessary with an equivalent single-range equipment. Another advantage accrues from the fact that the motor may be operated at an intermediate speed as a simple induction motor. The use of an independent auxiliary set permits of standardized designs and high speeds, factors minimizing first cost. The Scherbius system is at its best on 25-cycle systems and for moderate speed ranges.

FREQUENCY CONVERTER SYSTEM

Methods.—The frequency converter system of speed control resembles the Kramer and the Scherbius systems in that a counter-voltage at slip frequency is introduced into the secondary circuit of the main motor and this voltage is varied to change the speed. There are two methods of application, one giving a constant torque capacity, the other affording constant horsepower.

Both of these systems employ a frequency converter which is similar in principle to the ohmic drop exciter used in the Scherbius system. This unit is used however to convert the frequency of the slip energy of the main motor, rather than serving as an exciter.

Constant Torque System.—In the constant torque system the frequency converter is mounted on the common shaft with the main motor. It is wound for the same number of poles. The brushes may be located so as to supply either 3-phase or 6-phase current. The collector rings of the frequency converter unit are connected to the main power supply system through a transformer or regulator arranged to vary the voltage supplied to the converter. At the brushes of the converter may be taken off 3-phase or 6-phase voltage as desired, according to the brush arrangement. The frequency of this voltage is

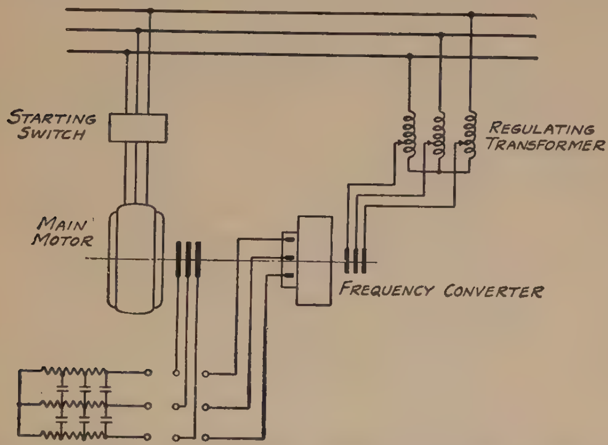


FIG. 56.—Principal connections for frequency converter system of speed control, constant torque type.

proportional to the difference between the frequency applied at the collector rings and the frequency of mechanical rotation. The voltage taken off at the commutator is proportional to that impressed at the collector rings. In these features the performance of this converter duplicates the action of the ohmic drop exciter.

As above stated, the frequency converter supplies an adjustable voltage at a frequency proportional to the slip. This frequency is the same as the slip frequency of the main motor since the primary of the main motor and the collector rings of the frequency converter are both supplied from the

same system, both machines are wound with the same number of poles and both are mounted on the same shaft and must rotate together. Therefore the voltage produced at the brushes of the frequency converter is suitable for introduction at the slip rings of the main motor to serve as an adjustable counter-voltage. Figure 56 shows the principal connections for this system which are seen to be quite simple.

With this arrangement the slip energy of the main motor is converted in frequency and returned to the supply system. When running above synchronism the reverse is true as power is then taken from the supply system by the frequency converter and furnished to the rotor of the main motor. At about synchronous speed the converter supplies direct current at the slip rings of the main motor. It should be evident that this drive has a greater horsepower capacity at high speeds than at low speeds. At speeds below synchronism, but a portion of the input is converted to mechanical power. At speeds above synchronism both the stator and rotor input are converted to useful work. The converter unit produces no torque.

Constant Horsepower System.—Equipments providing a constant horsepower are more frequently desired than those producing constant torque capacity. Moreover, the set above described is at a disadvantage in that a special type of frequency converter must be supplied having a speed corresponding to that of the main motor which is usually a rather low-speed unit. For these reasons the constant horsepower system has points of vantage.

In the constant horsepower arrangement the frequency converter unit is separately driven at constant speed by a small synchronous motor which supplies the losses of the unit. Another synchronous machine is mounted on the common shaft with the main motor. The last-named machine is made to produce an adjustable voltage by controlling its excitation. The frequency of this voltage is proportional to (1–slip). This variable voltage at variable frequency is impressed at the collector rings of the frequency converter which is driven at constant speed. The frequency taken off at the brushes of this unit is proportional to the difference between the speed of rotation and the frequency impressed on the collector rings.

It is thus proportional to the slip of the main motor. We then have an adjustable voltage at slip frequency which serves as a counter-voltage when applied at the slip rings of the main motor. The principal connections of this system are shown in Fig. 57. A motor unit, with wound-rotor and synchronous

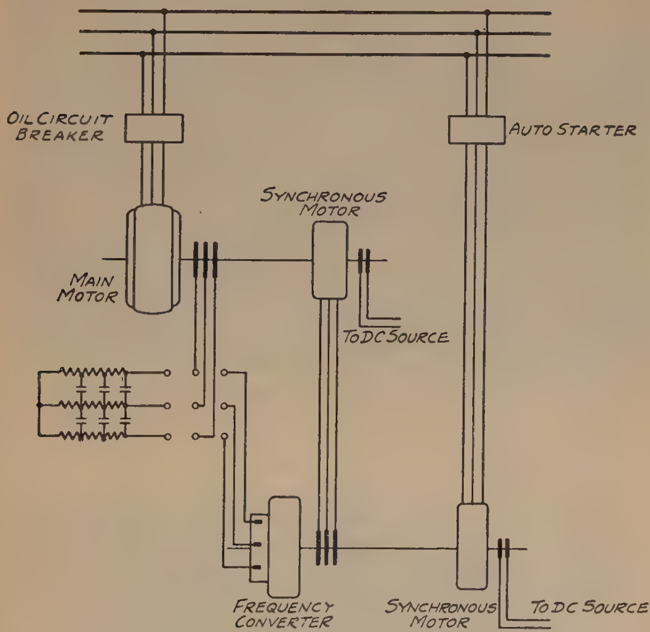


FIG. 57.—Principal connections for frequency converter system of speed control, constant horsepower type.

motors mounted on a common shaft, is shown in Fig. 58, while a frequency-converter set is shown in Fig. 59. As the latter is a separate equipment it may be run at high speed and its cost minimized. Limitations are placed on this set, however, due to commutation considerations.

In this arrangement the slip energy of the main motor is simply converted by the frequency converter and introduced into the synchronous machine of the main set where it is converted to mechanical power. When operating above synchronism the synchronous machine is a generator supplying electrical

energy to the rotor of the main motor through the frequency converter. In either case the input to the main motor, less

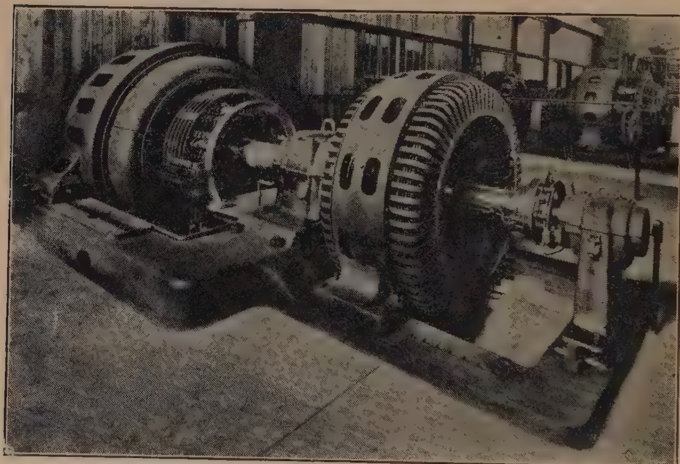


FIG. 58.—Motor unit for frequency converter system of speed control, showing wound-rotor induction motor and synchronous motor mounted on a common shaft.

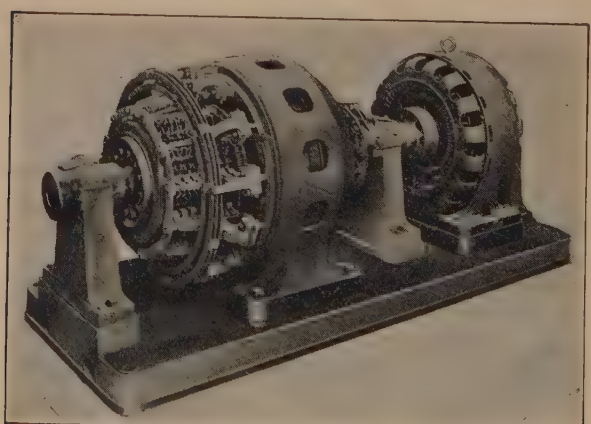


FIG. 59.—Frequency converter set for adjustable speed drive.

the losses, is converted to mechanical power at the common shaft. As the permissible input is a limiting factor, approximately the same horsepower is available at all speeds.

Operation above and below Synchronism.—As already intimated, both of the frequency converter systems above described permit operation under full load both above and below synchronism and also at synchronism. They thus duplicate the performance and enjoy much the same advantages as the Scherbius system in this regard.

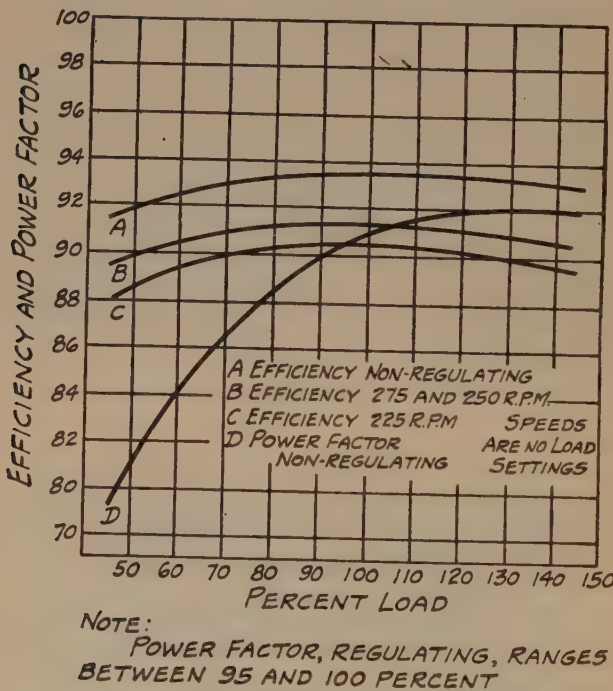
Power Factor Correction.—It is possible to correct the power factor of the main induction motor of a set of this type by causing the voltage supplied by the frequency converter to be somewhat out of phase with the secondary voltage of the main motor. This may be accomplished by shifting the brushes of the frequency converter. To maintain a constant power factor, the extent of brush shift required varies at different speeds. In order to avoid the necessity of actually shifting the brushes the equivalent effect can be obtained with the constant horsepower set by shifting the center line of the field poles on the synchronous motor driving the frequency converter. This is done by governing the excitation in the different sections of distributed field windings.

DYNAMIC CONTROL CHARACTERISTICS

Applicability.—In general, dynamic control is applicable to large units only because of the amount of auxiliary equipment required. For small units it is more simple to convert to direct current and provide adjustable speed motors. Very large units involve power in quantities too large to permit of easy conversion, transmission or distribution as direct current at low voltage.

Performance.—The operation of dynamic-control sets is not complicated. The initial cost is necessarily high because of the number of units involved. The speed-torque characteristics obtainable are parallel to those obtained from direct-current adjustable-speed shunt motors. The pull-out torque when operating with auxiliaries is usually greater than two times full-load torque and is thus comparable to operation on resistance. Since the motor starts as a wound-rotor motor on resistance the starting conditions are satisfactory. The efficiency is much higher than obtainable with rheostatic con-

trol due to the utilization of slip energy but, due to losses in the auxiliary units, the efficiency is lower at speeds wide from synchronism. It is possible to correct the power factor with any of the dynamic-control methods but this is feasible only to a limited extent. The power factor of the set therefore depends largely upon that of the main motor and is lowest with



(*Courtesy, J. D. Wright, Gen. Elec. Review.*)

FIG. 60.—Efficiency curves for a Scherbius set.

slow-speed, 60-cycle motors. Figure 60 gives curves showing the efficiency and power factor of a Scherbius set over a range of conditions. The performance shown is quite typical of dynamic-control sets in general.

Dynamic control is the only method yet devised for securing satisfactory adjustable constant-speed characteristics from alternating-current motors. These sets have been applied quite extensively for main roll drives in steel mills. They

have also found some applications on mine fans and elsewhere. It should perhaps be noted that they are not adapted where rapid changes in speed are required but are restricted to fairly constant running, adjustable-speed service.

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CHAPTER VII

THE POLYPHASE SYNCHRONOUS MOTOR

When two alternators are operating in parallel and not delivering any load, if each machine is excited to give the same terminal voltage, no current should flow, as their voltages are of the same value and are in exact phase opposition. If the prime mover of one machine is shut off, the unit will continue to run, the alternator operating as a motor and driving its prime mover. The tendency of this machine is to fall behind the unit which is supplying power and it does fall behind to some extent. This action brings the voltage of the motor unit a few degrees from direct opposition to the voltage of the generator unit so that the resultant of the two voltages is no longer zero. The resultant voltage forces a current through the impedance of the two machines. This current is such as to cause the production of torque in each machine; the torque in the generator unit opposes rotation, that in the motor unit maintains rotation. A synchronous motor is, in theory, a synchronous alternator receiving instead of producing electric energy.

The synchronous motor, in its prevailing form, is similar in structure to the revolving field alternator. This will be seen from Figs. 61 and 62. The stator, Fig. 61, presents a smooth bore and carries distributed phase windings, being similar in this respect to both the alternating-current generator and the polyphase-induction motor. The rotor, Fig. 62, comprises a number of radial pole pieces magnetized by coils carrying direct current introduced through collector rings.

Principle of Action.—The action of the synchronous motor is most readily explained as based on the fact that magnetic poles of unlike polarity attract each other. The number of rotor poles corresponds to the number of poles per phase in the

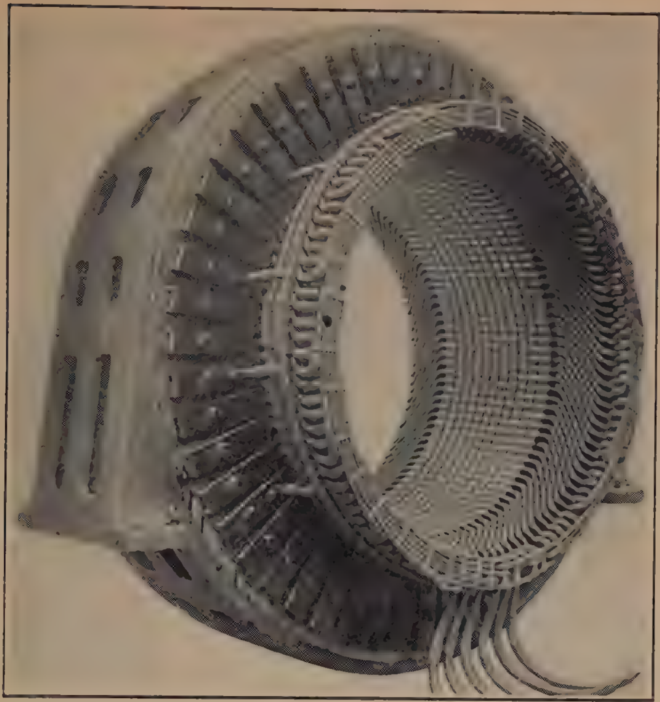


FIG. 61.—Stator of a revolving field-type synchronous motor.

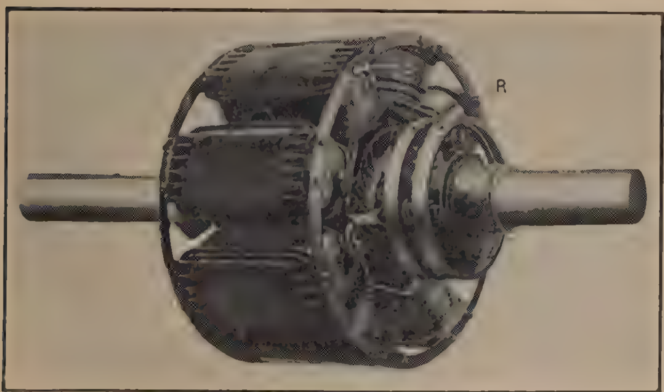


FIG. 62.—Rotor of a revolving field-type synchronous motor.

stator winding. Each south pole of the rotor tends to take a position directly opposite a north pole of the stator and vice versa. This action is identical with that of the compass, which takes a position in line with the magnetic field in which it is placed. (This condition is indicated in Fig. 63, in which the axis of the rotor poles corresponds with the axis of the stator poles.) The magnetic field, set up by magnetizing currents in the phase windings of the stator, revolves at synchronous speed, in the same manner as that of an induction motor. In order that the rotor poles may maintain their positions opposite the stator poles, they must also revolve at the same speed as the revolving field, namely at synchronous speed. The rotor must revolve in exact synchronism with the revolving field of the stator if uni-directional torque is to be obtained. At any other speed the rotor poles will pass alternately under unlike and like stator poles and torque at one instant will be forward, the next instant reversed. The synchronous motor derives its name from the fact that the rotor revolves at synchronous speed, regardless of the load.

Torque Production.—The torque developed by a synchronous motor is adjusted to the applied load according to the relative position taken by the axes of the rotor poles with respect to the polar axes of the revolving field set up by the magnetizing current in the stator conductors. When the motor is running without load, the axes of the rotor poles approximately coincide with the axes of the stator poles as indicated in Fig. 63. The forces of magnetic attraction are here entirely radial and no torque is developed. When load is added, the rotor lags slightly, not in speed but in angular position as shown in Fig. 64. The forces of magnetic attraction then have tangential components which develop torque. As the displacement increases, the tangential pull increases, not proportionately but in a decreasing measure. If the rotor poles should drop back 180 magnetic deg. like poles would be opposed and no torque would be produced. The torque developed as the revolving rotor poles drop behind and follow the revolving poles of the stator field, increases with the angular displacement until such displacement reaches an angle of 90 magnetic deg. Beyond this point operation becomes unstable as the

torque-producing power diminishes, and the motor pulls out of step.

Similarity to Other Motors.—The action of the synchronous motor is readily explained by the theory of magnetic attraction. This explanation fails, however, to show the likeness between this type of motor and all other motors in the fundamental characteristic of torque production by reaction between current-carrying conductors and a magnetic field. This similarity is, perhaps, most readily seen in the form of synchronous motor having fixed field poles and a revolving armature. The synchronous converter (rotary-converter) is an example of this general type of machine. A synchronous converter with the direct-current brushes raised from the commutator is, in effect, a synchronous motor. The field poles are fixed and excited by direct current, just as in a direct-current motor. The armature winding is practically the same as that in a direct-current motor except that leads are brought out to collector rings which are connected to a polyphase source of supply.

Torque is produced in a direct-current motor by reaction of conductors carrying current and located in the flux set up by the field poles. In order that this torque may be unidirectional the current in a given conductor must flow in one direction when that conductor is under a north pole and in the other direction when that conductor is under a south pole. By means of a commutator the direct-current external supply is converted into reversing, *i.e.*, alternating current within the armature conductors. The direct-current motor is operative at any speed because the rate of reversal of current flow (frequency) in the armature conductors is proportioned to the speed automatically by the commutator which revolves at the same speed as the armature. For any given speed there is a definite frequency of voltage generated and current flow in the armature conductors, corresponding to the rate at which a given conductor passes alternate north and south poles of the fixed field.

If the commutator of a direct-current motor be replaced by collector rings suitably connected to the windings and if alternating current be introduced directly into the armature rather than indirectly by commutation of direct current, the

conditions are unchanged, with the exception that the motor is operative at a single speed only. The speed of rotation must be such that the current reversals take place in the conductors at a rate corresponding to their passage under alternate north and south poles. At any other speed uni-directional torque will not be produced.

From the above explanation it is evident that the synchronous motor is similar, in the fundamentals of torque production, to other motors. As action is equal and opposite to

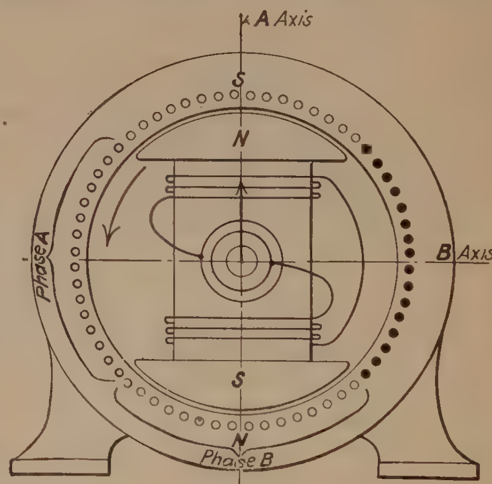


Fig. 63.

Synchronous Motor, slightly underexcited, operating with zero load. (Theoretical because there is always some load.)

At the instant shown:

1. Supply voltage in phase A is zero.
2. Magnetizing current in phase A is maximum. Rotor is assumed to be slightly underexcited so that magnetizing current flows in a direction to assist the rotor field.
3. Revolving field is maximum on A axis.
4. Supply voltage in phase B is maximum.
5. Magnetizing current in phase B is zero.

There is no load current in either phase.

reaction and as motion is relative, it is immaterial whether the fixed member is the field or the armature or vice versa. This will be most readily realized in view of the fact that the frame of any motor carrying load requires holding-down bolts to prevent it from rotating and rolling over.

Magnetizing Current Relations.—When voltage is applied to the stator of a revolving field type of synchronous motor, such as shown in Figs. 63 and 64, with the rotor field circuit open, magnetizing currents will flow in the stator windings,

setting up the revolving field. These magnetizing currents are in time quadrature with their respective voltages. Due to the reversing field on any fixed axis of the stator, a back voltage is induced in the stator coils by self-induction, opposing the impressed voltage. The back voltage is less than the impressed voltage by an amount just sufficient to cause the magnetizing current to flow. This action is identical to that in the polyphase induction motor and that in the primary of the static transformer. When the motor is running, without load, at synchronous speed, with rotor fields excited by direct current, the poles are practically in line with the axes of the stator poles as shown in Fig. 63, in which the axis of the rotor poles corresponds to the axis of the stator field set up by magnetizing current in phase A. The rotor poles, of fixed polarity, revolving in space at synchronous speed, tend to set up a flux which is alternating with reference to any fixed point or axis of the stator. When the rotor poles coincide with the stator poles, the magnetizing forces of stator and rotor are directly cumulative (or opposed). If the rotor excitation be such that it tends to set up a field of exactly the strength required to give the condition of equilibrium between impressed and induced voltages in the stator windings, no magnetizing current need flow in the stator conductors to supply the required magnetization. If the rotor excitation is less than that necessary to set up a flux of required strength, sufficient lagging magnetizing current will flow in the stator conductors to supply the deficiency in magnetization. If the rotor excitation exceeds that necessary to set up a flux of required strength, the induced voltage will exceed the impressed voltage by a small amount and a leading magnetizing current of reverse sense will flow, opposing the rotor's magnetization and thus restricting the flux to an amount which will retain the condition of equilibrium between induced and impressed voltages. The excess magnetization supplied by the rotor is transferred to the alternating-current system in the form of leading current.

Load Current Relations.—When load is applied to this motor, the rotor poles fall back and become angularly displaced with respect to the stator poles, *i.e.*, the axis of the revolving field. This condition is shown in Fig. 64. The rotor's magnetizing

force is then not directly in line with the stator's magnetizing force. The rotor's magnetizing force may be considered as comprising two components, one along the axis of the stator's field, the other at right angles (90 magnetic deg.) therewith. The quadrature component of the rotor magnetization may be conceived as tangential and is thus the torque-producing component. That component in line with the stator field influences

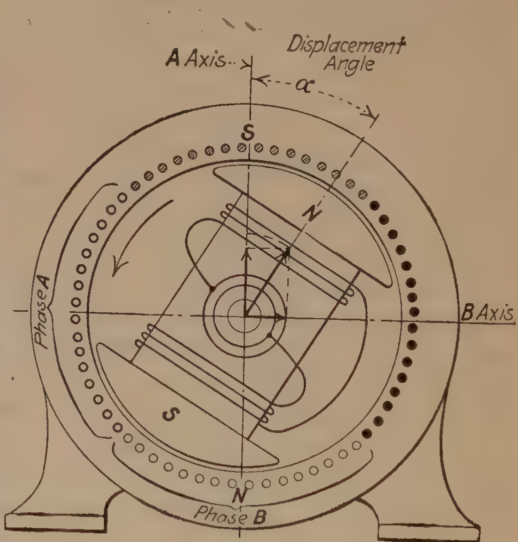


FIG. 64

Synchronous Motor (underexcited) with poles on load position.

At the instant shown:

1. Supply voltage in phase A is zero.

2. Magnetizing current in phase A is maximum.

Rotor has same excitation as in Fig. 63. As the component along the A axis is reduced, an increased assisting magnetizing current flows in phase A.

3. Revolving field is maximum on A axis.

4. Supply voltage in phase B is maximum.

5. Magnetizing current in phase B is zero.

6. Load current is taken by phase B to neutralize the component of rotor magnetizing force along the B axis. This current is maximum.

the magnetizing current in the stator winding. The magnetizing force of the other component must be neutralized by an equal magnetizing force set up by the stator in order to maintain the condition of equilibrium previously mentioned. In order that stator currents may neutralize this quadrature component of rotor magnetization, their magnetizing influence must be in line with this component. It will be seen in Fig. 64 that this line of magnetization corresponds with the axis of any magnetization which might be set up by current flowing

in coils of phase *B* at this instant. A current is actually drawn from the line and flows in phase *B* such that it neutralizes the magnetizing force due to the quadrature component of the rotor's magnetization. We are considering the instant when voltage impressed on phase *A* is zero and that impressed on phase *B* is maximum. Quite evidently, the current in phase *B* above mentioned is in phase with the voltage of phase *B* and is thus a power current. At other instants a similar relation holds with respect to phase *A*.

In summarizing, it may be said that when load is applied and the rotor poles become angularly displaced, the component of rotor magnetizing force which is in quadrature with the axis of the stator's revolving field, causes a neutralizing current to be drawn from the supply, the phase of this neutralizing current being such that it represents power intake. Two current components flow within all the stator conductors. One current, the magnetizing component, is lagging or leading. This cooperates with one component of the rotor magnetizing force to set up the revolving field and to maintain it at a fixed value (neglecting leakage, etc.). The other current, the power component, offsets or neutralizes that component of the magnetizing force of the rotor which is due to its displacement by the load.

It should be recognized that the action within the stator windings is identical with that occurring in the stator windings of a polyphase induction motor. The load component of the rotor magnetizing force in the synchronous motor corresponds to and replaces the magnetizing force in the induction motor's rotor which is set up by the rotor's load current.

Effect of Load on Magnetizing Current.—If a synchronous motor, operating without load, is so excited that no wattless magnetizing current is taken, the power factor of the motor is unity. If a load be added, the rotor poles are displaced (Fig. 64). Only one component of the rotor field is now effective in maintaining the required revolving field. Obviously, this component is less than the total rotor magnetizing force. It is thus insufficient to maintain the revolving field at required value, hence sufficient magnetizing current is drawn from the line to supply the deficiency. Thus a motor excited to operate

at unity power factor without load will operate at a lagging power factor when load is applied.

Effect of Excitation on Torque.—Again consider a synchronous motor operating without load and excited for unity power factor. When load is applied the rotor is displaced and the quadrature component of the rotor field causes a power component of current to be drawn from the line (Fig. 64). The extent of the displacement is such that the quadrature magnetizing force causes the power intake from the line to correspond to the power demand at the motor shaft (plus losses). If the rotor excitation be increased (Fig. 65) both of its components are increased. If the angular displacement remained unchanged, the quadrature component would be greater than that in Fig. 64 and the power developed would be greater than required by the torque demand. Since the quadrature component must have a value proportionate to the load, the angular

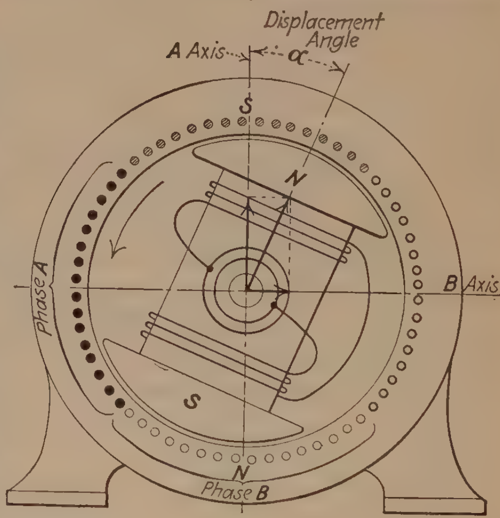


FIG. 65.

Over-excited synchronous motor carrying the same mechanical load as indicated in Fig. 64.

At the instant shown:

1. Supply voltage in in phase A is zero.

2. Magnetizing current in phase A is maximum.

Rotor excitation has been increased to such an extent that the counter-voltage in phase A exceeds slightly the impressed voltage. Direction of flow magnetizing current is reversed.

3. Revolving field is maximum on A axis.

4. Supply voltage in phase B is maximum.

5. Load current is taken by phase B, same amount as in Fig. 63. This current is maximum.

Note that displacement angle is less than in Fig. 63.

displacement decreases until the quadrature component is just sufficient to meet the torque requirement and to cause the corresponding load-current intake. The greater the rotor excitation, the less angular displacement is necessary to develop the required tangential component of magnetizing force. Increase in primary voltage, leading to higher magnetization, also minimizes the rotor lag for a given torque production.

Short-circuit Ratio.—The displacement angle assumed by a motor with a given load and excitation depends materially upon the synchronous impedance of the armature or stator. This is made up of the resistance of the stator windings, their self-inductance and the magnetizing effect of the current in the stator windings on the field, the latter effect being commonly termed armature reaction.

The short-circuit ratio of a synchronous motor may be defined as the ratio between the field current giving unity power factor at no load, normal voltage, and the field current necessary to establish rated amperes per terminal on short circuit. It is a measure of the relative magnetizing power of the stator and rotor windings. In an alternating-current generator it is desirable to have a relatively strong field and low-armature reaction to give fair voltage regulation, to permit the development of full voltage at low power factor and to obtain synchronizing power between machines. On the other hand, high armature reaction reduces the current on short circuit.

In a self-starting synchronous motor it is desirable, partly in order to minimize the magnetizing current taken during starting and to increase the starting torque, that a relatively short air gap be used. With a shortened air gap, the necessary magnetizing power of the field or rotor is reduced. The ratio of field to armature magnetizing strength is relatively low and the armature reaction is high. High armature reaction tends to give both a high starting torque and a high pull-in torque. A motor with high armature reaction will carry a considerable part of its rated load without direct-current excitation, all of the magnetization being supplied by the armature or stator. On the other hand, high armature reaction leads to a wide displacement angle for a given load and reduces the

maximum torque. A wide displacement angle involves comparatively large change of rotor field component in line with the axis of the magnetic field, for a change from no-load to full-load, thus involving considerable change in magnetizing current or power factor with load changes. High armature reaction makes a motor more sensitive to changes of load and line voltage. A compromise is evidently necessary between requirements favorable to induction-motor action and requirements favorable to synchronous-motor action. The short-circuit ratio in synchronous motors will usually have a value between 1 and 2.

The magnetizing current taken by a synchronous motor when running on full line voltage at synchronous speed without rotor excitation, is equal to full-load current times the short-circuit ratio. This current is ordinarily 110 to 150 per cent of full-load value, being greater for low- than for high-speed motors. This compares with a magnetizing current of 25 to 60 per cent full-load current taken by standard induction motors. The magnetizing current taken by a synchronous motor operating as an induction motor below synchronous speed is also relatively high and the power factor low.

Speed.—The speed of a synchronous motor is the same as the speed of the revolving field. This is determined, as in the induction motor, by the circuit frequency and the number of poles per phase in the stator winding. The speed is equal to 120 times cycles per second divided by the number of poles per phase. On a circuit of fixed frequency the synchronous speed is constant and the motor operates at this speed regardless of load up to its point of maximum or pull-out torque.

Direction of Rotation.—The direction of rotation is determined by the direction of the revolving field. This, in turn, is governed by the phase relations in the stator windings, just as in the induction motor. A three-phase motor may be reversed by interchange of any two stator leads. Reversal of the direct-current field leads does not affect the rotation but merely influences the angular position of the rotor to the extent of one pole space.

Excitation.—The direct current necessary for excitation of the rotor fields may be taken from any suitable direct-

current supply. More commonly a small exciter is provided, either direct-connected or belt-driven by the motor. Synchronous motor-generator sets converting to direct current up to 275 volts commonly take their excitation from the direct-current end of the set. For reasons later explained, 125-volt excitation may be preferable to excitation at higher voltages. A field rheostat is commonly supplied in the exciter- or motor-field circuits, or both, for adjustment of the excitation. In the case of motors to be operated at 100 per cent power factor the motor rheostat is often omitted.

Power Factor Correction.—Previous mention has been made that either magnetizing or demagnetizing wattless current may be taken from the supply system, depending upon the degree of direct-current excitation. Thus it is possible to govern the power factor of the motor by adjusting the field current. This is a unique characteristic and is one of the most important attributes of the synchronous motor.

Synchronous motors may be operated to carry mechanical load only. They may be operated as synchronous condensers for power factor correction or voltage regulation with no mechanical load, or they may perform both services simultaneously. The degree of excitation required depends upon the service for which the machine is intended. Figure 66 gives the so-called V curves of a synchronous motor. These curves show how the stator current changes with different degrees of excitation. With a given load, a definite excitation results in minimum armature or stator current. This condition corresponds to 100 per cent power factor. At other excitations there is more or less lagging or leading wattless current, the amount depending upon the departure from unity-power-factor excitation. These curves show the relations for no-load operation, for operation with half rated mechanical load and with full rated mechanical output. The full lines apply to armature current values; the dotted lines show corresponding values of power factor.

The shape of the V curves depends largely upon the value of armature reaction, the curves coming to a sharp point for minimum input and rising rapidly on either side with slight change of field excitation in the case of a machine with low

armature reaction. The V curves are much flatter in the case of a motor with high armature reaction, due to the fact that a relatively small change in magnetizing current, hence power factor, will compensate for a given change of excitation.

When a synchronous motor is operated to carry mechanical load only, its field is best excited to such a point that the power factor is unity at full load. The absence of wattless current permits minimum current input and highest efficiency under these conditions. As the mechanical load changes, the power factor will vary slightly. A machine may have a slightly leading power factor with a given excitation under light load. As the load increases, the rotor poles fall back so that they are not so nearly opposite the stator poles and their magnetizing influence is less effective. Unity power factor conditions will then be approached. Still further increase of load may even cause a lagging current to flow. Well-designed motors do not vary their power factor appreciably with changes of load. Since operation is more stable with over-excited fields and since the power factor tends to lag with increase of load, it is sometimes advisable to slightly over-excite the fields, particularly with fluctuating loads.

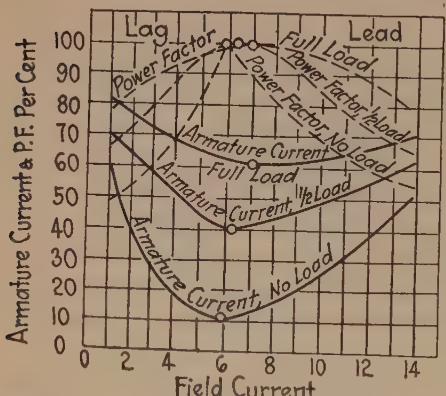


FIG. 66.—V curves of a synchronous motor, showing relations between excitation and armature current and power factor.

If a synchronous motor is to be operated idle, without load, for power factor correction only, it may be built lighter in some respects, having a smaller shaft and bearings, for instance. Such a machine is not in reality a motor at all, being more correctly termed a synchronous condenser. The field excitation may be varied to such an extent that the armature current attains its full rated value, being almost entirely wattless.

In this case the condenser exerts its maximum corrective influence and operates at almost zero power factor. If it is simply desired to raise the power factor of a system to a definite value, the excitation may be adjusted for a lesser amount of wattless current, just sufficient to accomplish the purpose. If the power factor of the system varies, this adjustment may be made automatically, if desired, by means of a regulator.

Synchronous motors which are to be used to drive a mechanical load, with no power factor correction other than that resulting from addition of unity power factor load to the system, are rated on a 100 per cent power factor basis. Motors which are to be used for combination service are rated on the basis of k.v.a. input at any required power factor, more commonly at 80 per cent.

If a synchronous motor is to be used for combination service, to carry a mechanical load and also to correct the power factor, it must be larger than if it were to perform either service alone. When operating near 100 per cent power factor the capacity of the motor is limited by the heating of the stator conductors. When operating with leading power factor the capacity of slow- and medium-speed motors is limited by field heating. When the machine is carrying load at 100 per cent power factor, no wattless current is involved, so that the current is all effective in producing mechanical output. Operating as a synchronous condenser at low power factor, the current is nearly all wattless. With combined service, both load and wattless components exist. When the motor is operated at about 70 per cent leading power factor, approximately 70 per cent of the input k.v.a. is available for supplying energy current and 70 per cent available for supplying wattless current. At higher power factors, a greater proportion of the input is available for energy load and materially less is available for supplying wattless current and vice versa. A combination unit is most effective when carrying some mechanical load. The exact relation as to mechanical load and wattless component which will give maximum corrective influence is affected by the size and power factor of the system to which the motor is connected. It is also influenced by the motor's short-circuit ratio. For further discussion of the subject of power factor correction by synchronous motors, the

reader is referred to some excellent articles mentioned in the bibliography. Combination service is efficient in that dual purposes are accomplished in a single unit almost as effectively as if the unit were used for but one service.

Cognizance should be taken of the fact that the synchronous motor has a high power factor only when properly excited. It is quite possible, through carelessness, to obtain a poorer power factor with the synchronous motor than that normal to the induction motor. Proper attention is thus essential.

Maximum Torque.—As previously stated, increase of torque demand causes the rotor to lag and the displacement angle to

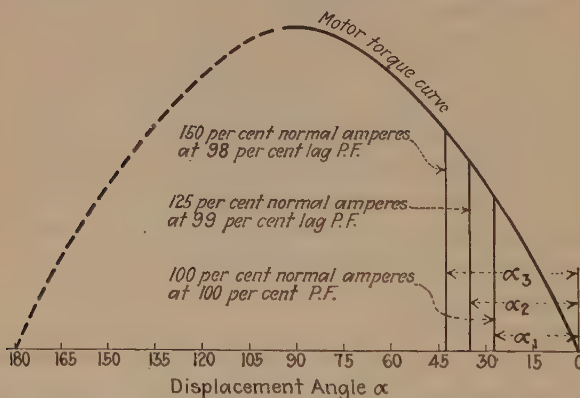


FIG. 67.—Relations of torque to angular position of fields in a synchronous motor excited for 100 per cent power factor at full load.

increase. The torque production for a given displacement is proportional to the quadrature component of rotor magnetizing force corresponding to that displacement (with fixed excitation). For small angles of displacement, the increment of quadrature component is relatively large. As the angular displacement increases, the increment of quadrature component corresponding to a given increase in angular displacement, decreases. (In Fig. 64, the quadrature component is the horizontal projection of the rotor magnetizing force. Evidently this increases less rapidly for a given increment of angular displacement as the angle increases.) Quite evidently the relation between torque and angular displacement is shown by a sine curve, as

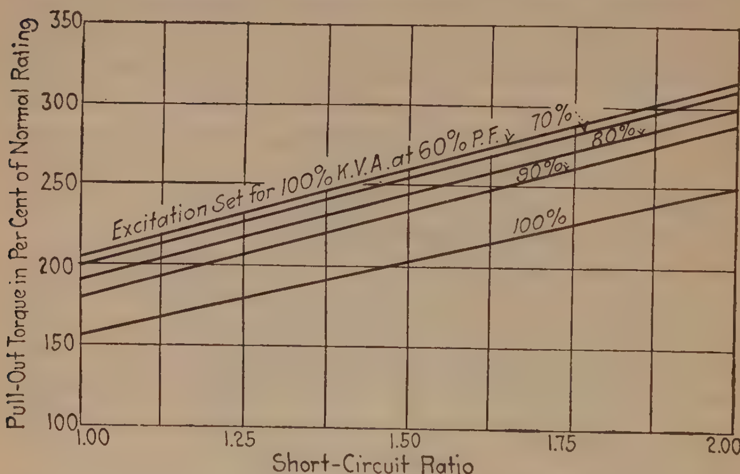
indicated by Fig. 67. When a displacement of 90 deg. is reached the motor exerts its maximum or pull-out torque. The maximum torque developed by a synchronous motor is increased materially if the fields be strongly excited, since the displacement angle for a given torque is decreased and greater torque is thus required to cause 90 deg. displacement. The maximum torque, with fixed excitation, varies directly as the impressed voltage. If the excitation is varied to correspond with the variation in applied voltage, the maximum torque varies as the square of the impressed voltage. In a motor with fixed excitation, the usual case, a drop in voltage causes the motor to draw leading current and assume an overexcited condition which tends to maintain the driving torque so that the decrease is less rapid than in the case of an induction motor. This gives the synchronous motor some advantage where the line voltage is unsteady.

The maximum torque is influenced directly by the short-circuit ratio. Just as high armature reaction decreases the synchronizing power of alternating-current generators, so does it reduce the pull-out torque of a synchronous motor. Thus, the greater the relative field strength and the larger the short-circuit ratio, the greater is the pull-out torque. The relations between pull-out torque, excitation and short-circuit ratio are indicated in Fig. 68, which shows a set of calculated values of pull-out torques with gradually applied load. External reactance in the circuit supplying a synchronous motor has an effect equivalent to increase of synchronous impedance and decreases the pull-out torque.

Synchronous motors operated at unity power factor commonly develop 150 to 300 per cent full-load torque before pulling out. This can be materially increased if need be. They will withstand a considerably higher torque of momentary duration than if gradually applied. Unnecessarily high pull-out torque is not desirable as it is usually obtained at the sacrifice of other characteristics. The pull-out torque of the ordinary synchronous motor is limited principally by field heating. The requirement of heavy overload torques usually necessitates increased field flux, larger magnetic circuit and heavier field copper, hence may involve a larger frame and higher cost.

Similar requirements arise in motors operated overexcited for power-factor correction. The extra capacity required for overload torque development can be used to good advantage to improve power factor.

Starting Performance. *Auxiliary Machine.*—The synchronous motor develops torque due to pure synchronous-motor action only when running at synchronous speed. It was formerly customary to accelerate these motors from rest by



Courtesy, Theo. Schou.

FIG. 68.—Relations between short-circuit ratio, excitation and pull-out torque.

means of a small auxiliary induction motor or, in the case of a motor-generator set, to utilize the direct-current end of the unit for this purpose. If an auxiliary induction motor is used, it has fewer poles than the synchronous motor so that its synchronous speed is greater than that of the larger machine. Primary voltage control is then commonly applied to the auxiliary unit in order to adjust the speed to permit synchronizing the larger motor. Equipments of this type are intended to start without load, thus minimizing the size of the auxiliary motor.

Self-starting Motors.—The great majority of polyphase synchronous motors are now of the self-starting type. These

motors function as induction motors during the starting period, synchronous-motor action becoming effective at speeds slightly below synchronism. Since an induction motor never attains synchronous speed, it follows that a motor cannot be brought to synchronous speed purely through induction-motor action. At speeds below synchronism impulses are set up by synchronous-motor action, that is, attraction and repulsion between unlike and like poles of stator and rotor. As the rotor poles slip past the stator poles these impulses are alternately favorable and then opposed to the rotation. As the slip decreases these impulses become greater in magnitude and duration. If the motor is accelerated, by induction-motor action, to a speed sufficiently near synchronism, say within 3 to 6 per cent, these impulses attain such magnitude that, if the load and inertia to be accelerated are not too great, the motor will be pulled into and held in step by the synchronous-motor torque. The nearer the motor approaches synchronous speed by induction-motor action, the greater and more prolonged are the synchronizing-torque impulses and the less is the inertia an obstacle to pulling into step.

Development of Starting Torque.—Since the synchronous motor functions as an induction motor in starting, its performance is then governed largely by the measure in which it attains the design features of induction motors having good starting characteristics. Practically all self-starting synchronous motors are provided with a squirrel-cage winding embedded in the field-pole pieces, as shown in Fig. 62. This winding is the principal factor in the development of starting torque although some torque is added due to hysteresis and eddy currents in the field poles themselves. Currents induced in the rotor-field coils, if their circuit is closed, produce a torque which assists the rotation up to half-synchronous speed and opposes the rotation at higher speeds. This torque decreases as synchronism is approached and becomes zero at synchronous speed.

Compromise Design.—Since a self-starting synchronous motor must perform both as a synchronous and as an induction machine, the design is generally a compromise. A narrower air gap may well be used and this, in turn, permits a wider pole face and less space between poles. These features improve

the action as an induction motor without serious detriment to the synchronous performance. The principal influence of a short air gap on the action as a synchronous motor is to increase the synchronous impedance, decrease the short-circuit ratio and decrease the pull-out torque. Also, with short air gap, the variation of power factor with load change and constant excitation is accentuated. In high-speed machines with wide stator slots and short air gaps large pole face losses may result due to pulsations in the magnetic flux caused by the wide slots.

Resistance of Cage Winding.—Factors which lead to high starting torques in the induction motor are low magnetic leakage and high secondary resistance. The magnetic leakage in a synchronous motor is necessarily high as a fairly wide air gap is desirable for the synchronous design. The use of definite poles as contrasted with the smooth drum rotor of the induction motor also tends to increase magnetic leakage. On the other hand, a high rotor resistance may be used if desired. The rotor resistance of the squirrel-cage induction motor is normally made quite low in order to restrict the rotor losses to maintain good efficiency and to prevent undue heating. Consequently the standard squirrel-cage induction motor is somewhat deficient in starting torque. The cage winding of the synchronous motor functions only during the starting period, hence the secondary losses are of importance only from the aspect of heating and not as affecting running efficiency. It is not exceptional to find synchronous motors with high-resistance cage windings which will develop starting torques equaling or exceeding those which would be developed by squirrel-cage induction motors of similar rating.

In order that a synchronous motor may pull into step, it is necessary to accelerate it until synchronous speed is quite closely approached. The nearer this approach the more powerful is the synchronizing action. The slip of an induction motor depends upon the load and also upon the resistance in the cage winding. If a high cage resistance be used in order to provide a high starting torque, it is quite possible that the slip will be so great that sufficient synchronizing action cannot be developed to pull the motor into step. In Fig. 69 are shown the starting torques developed on 50 per cent primary voltage

by a motor with cage winding of high resistance using brass bars and also with a cage winding of low resistance using copper bars. It is quite evident that the high-resistance cage winding gives the higher starting torque but that the low-resistance cage winding enables a greater load to be carried with a given slip or a given load with less slip. The high-resistance winding develops more torque per ampere input at starting but the low-resistance winding develops more torque per ampere input at speeds near synchronism. The design of the cage winding for

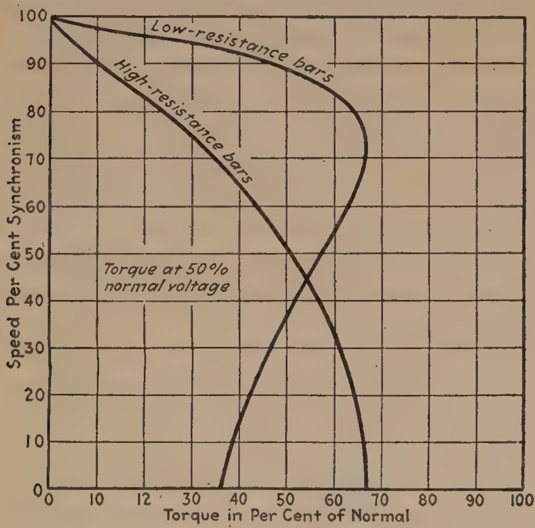


FIG. 69.—Starting torque of a synchronous motor with high-resistance and low-resistance squirrel-cage windings on the rotor.

a motor must be a compromise between these extremes and is governed largely by the characteristics of the load to be started. For instance, a centrifugal pump or blower requires a low starting torque, but the torque demand may increase rapidly with the speed. A motor with low-resistance cage winding is well suited for such an application. On the other hand, a pulp grinder may require a high torque to overcome static friction but a relatively low torque suffices to maintain rotation. For such an application a motor with high-resistance cage winding is adapted.

Use of Skin Effect.—The starting of a synchronous motor involves two distinct requirements, namely starting and pull-in torques. These requirements are more or less opposed in their design influence. Means have been devised and used by some manufacturers to obtain high starting torques without excessive slip. One method now practiced involves the use of tubular copper or brass bars in the cage winding. Within the tubes iron bars are embedded. When starting from rest, the frequency in the secondary or squirrel-cage circuit is the same as that of the primary, but as the rotor accelerates, the secondary frequency approaches zero. Due to skin effect, the inner bars of magnetic material are not effective as conductors when the rotor speed is low, but a high starting torque is obtained due to the high resistance of the copper or brass tubes used. As the rotor accelerates and the secondary frequency falls, the skin effect decreases and the effective resistance of the cage-winding decreases. Thus the motor is given the characteristic of a high-resistance squirrel-cage to develop good starting torque but also secures the advantages of a low-resistance cage in minimizing the slip.

Similar results may be secured by the use of deep rotor bars which have low resistance but high reactance at low speed when the rotor frequency is high. By this scheme the rotor impedance at low speed is made greater than at high speed, giving the motor the starting characteristics of a high-resistance rotor and the pull-in ability of a low-resistance rotor. This is further augmented by the action of eddy-current losses in the rotor bars. These losses vary with the depth of the bars and, as they are greatest when the secondary frequency is high, *i.e.*, at low speed, they assist in the development of high starting torque without materially affecting the slip when the rotor approaches synchronous speed.

Starting Performance.—As previously indicated, it is possible to design motors to develop high starting torque only or high pull-in torque alone, but it is more difficult to combine the two and not possible to obtain both features to maximum degree. High pull-in torque is the more difficult condition to meet. In general, high-speed designs exert somewhat better starting torques than low-speed designs. It is difficult to state

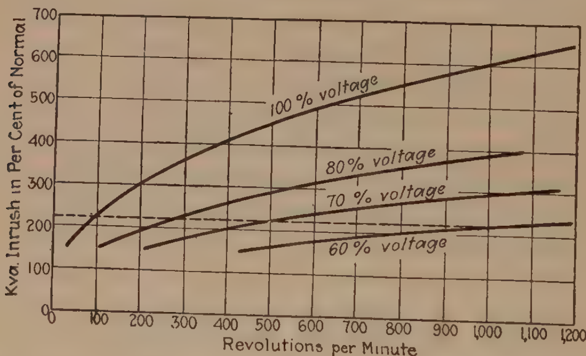
accurately what starting performance is representative as development is rapid and manufacturers' statements vary. The following values are probably fairly representative of the best performance generally available. Motors of 180 r.p.m. and above can be made to develop about 90 per cent pull-in torque at about 80 per cent voltage with a corresponding starting torque of about 35 per cent. Lower speed motors can be made to develop about 50 per cent pull-in torque under similar conditions. Motors of all speeds may be had to develop 100 to 150 per cent starting torque at about 80 per cent voltage but will have a correspondingly low pull-in torque of about 15 to 25 per cent. The corresponding starting peaks will be about 250 to 300 per cent k.v.a.

The synchronous motor is superior to the squirrel-cage induction motor in starting performance if a high starting torque and low pull-in torque are required and even when these two torques are about equal. The squirrel-cage induction motor is superior if the torque near synchronous speed is relatively high. The wound-rotor induction motor is superior to both.

Heating of Cage Winding.—One of the limiting factors in the development of high starting duty from self-starting synchronous motors is the heating of the squirrel-cage winding. The rather high resistance necessary to obtain high starting torque causes appreciable secondary losses. The cage winding cannot fully dissipate these losses and the heat storage capacity of this winding cannot be great as the winding must be inserted in and encroach upon the field pole pieces. For these reasons it is necessary that a self-starting synchronous motor be capable of accelerating its load to synchronism quickly, say in less than one minute, otherwise the cage winding may become overheated. In any case, a substantial construction of the cage winding is necessary to withstand the overheating which may be at least occasionally anticipated. This matter may be a consideration of particular importance in connection with drives involving high inertia as the need for rapid acceleration in turn increases the torque requirement.

Current Inrush.—Another consideration which limits the starting torque which may be secured from a self-starting synchronous motor is the heavy current inrush involved. This

inrush is particularly objectionable in that the power factor at starting is low. During this period the magnetization must be supplied from the alternating-current system. The starting torque developed per k.v.a. input by a synchronous motor with low-resistance cage winding will ordinarily be less than that of a standard squirrel-cage induction motor. The starting torque developed per k.v.a. of input by a synchronous motor with high-resistance cage, will ordinarily be higher than that of a standard squirrel-cage induction motor. When running near synchronism the synchronous motor will ordinarily draw a



Courtesy, Theo. Schou.

FIG. 70.—Starting current inrush of synchronous motors of different rated speeds and with different impressed voltages.

larger k.v.a. from the line than would a similar induction motor. This is due in part to the heavier magnetizing current required largely because of the wider air gap and definite pole construction. The power factor at starting is usually about 25 to 50 per cent. Owing to the heavy wattless current taken, the motor may require 200 to 400 per cent normal k.v.a. at starting if the load is appreciable. Since synchronous motors in general are of the larger sizes, the effect upon the generating system may be a serious consideration. In this connection Fig. 70 is of interest. This is typical of a line of motors of about 150-k.v.a. rating. It will be noted that the current inrush values are much lower for slow-speed motors than for high-speed motors. On the other hand, high-speed motors

commonly have better starting characteristics and may consequently be started on lower voltages. As the low-speed motors are usually of large size, it is fortunate that their starting current inrush is relatively low.

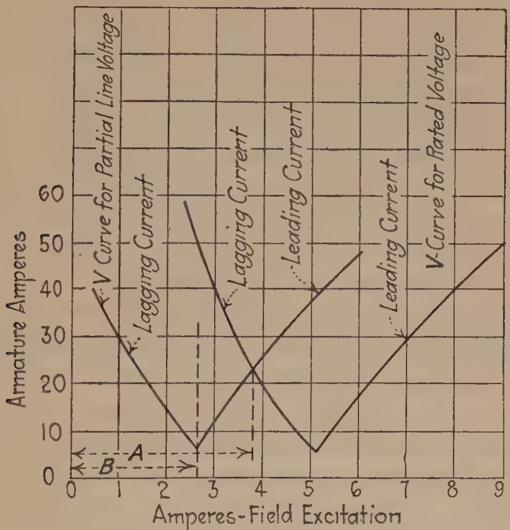
Starting Methods.—The operation of starting a self-starting synchronous motor is similar to the starting of an induction motor but is slightly more involved. In order to restrict the current inrush and to prevent too sudden impulse, reduced voltage is usually applied to the stator windings and, after the motor has reached or approached synchronous speed, it is transferred to full voltage. The reduced starting voltage may be obtained from autotransformers or taken from taps of the main transformers, if any, which feed the motor. It is usually desirable to apply in starting, as low a voltage as will insure the necessary torques, provided this voltage is not so low that the current peak when throwing to full voltage exceeds the initial inrush and provided acceleration is rapid enough to prevent overheating of the squirrel-cage winding.

When starting a synchronous motor from rest, an alternating flux passes through the field poles and causes to be induced in them a rather high voltage. This voltage is high, due to the comparatively large number of field turns in series. Obviously, it is higher if the fields are wound for 250-volt excitation than if 125-volt excitation be used. If the fields be short-circuited during the starting period, a current flows in them and this current restricts the flux and the voltage generated thereby. On the other hand, the reaction of this current tends, to some extent, to reduce the torque developed and may thus be undesirable. A compromise is usually made by short-circuiting the fields through a fairly high resistance. This practice restricts the voltage induced, yet minimizes the detrimental influence on motor torque. As this action depends upon the resistance in circuit, it may be desirable to adjust this resistance. This may be done by running the motor under load as an induction machine and adjusting the field short-circuiting resistor to give the highest attainable speed. Usually the fields are short-circuited through the field-discharge resistor or the field rheostat or the exciter or a combination of these is used.

Three methods of starting synchronous motors are in common use. Each has its advocates and it is probable that each has advantages for certain conditions.

Synchronizing on Partial Voltage.—In one method the motor is started on reduced voltage. If the load be light, it may pull into step while on partial voltage and without direct-current field excitation. In such case it functions as a synchronous motor with excitation supplied from the alternating-current system. Ordinarily, some excitation must be applied to assist the motor in pulling into step. This excitation should be applied when the motor has attained about 95 per cent of synchronous speed. This excitation should be sufficient to insure that the motor pulls into step with a polarity relation corresponding to the excitation applied. It is usually well to apply excitation about corresponding to that giving unity power factor with no load and full voltage. If the motor pulls into step with this excitation, full voltage is applied. Some motors tend to oscillate when excitation is applied and they pull into synchronism. Time must be allowed for the motor to become stable before transferring to full voltage, otherwise it may fall out of step. The current peak incident to the transfer operation is governed, to a marked extent, by the excitation applied. It is desirable that the excitation applied to pull the motor into synchronism on the low-voltage tap be adjusted to such a value that the motor is considerably overexcited with reference to its load on partial voltage. It then draws considerable leading wattless current. When the motor is transferred to full voltage it will be somewhat underexcited and will draw lagging current. If the motor were excited when running on low voltage, to an amount corresponding to its full voltage, full-load condition, it would be excessively overexcited with reference to partial voltage requirement and would draw a heavy leading current. A compromise is desirable between the leading wattless current taken on partial voltage and the lagging wattless current taken on full voltage. This condition is brought out clearly in Fig. 71, which shows the V curves of a motor both on partial and on full voltage. If the excitation be such as to correspond to the intersection of the two V curves, the minimum line disturbance is obtained.

The transfer from reduced voltage to full voltage must be accomplished quickly lest the time interval be sufficient to permit the rotor to slip back a pole. If this happens, the generated counter-voltage and the impressed stator voltage are cumulative and practically a short-circuit results, the current flow being limited only by the reactance in circuit. A similar shock may be produced by transferring to line voltage with the



Courtesy S. S. Mortensen, Proc. Western Society of Engineers.

FIG. 71.—No-load V curves on partial voltage and full voltage, showing effect of excitation on current taken when transferring from partial to full voltage.

rotor in synchronism but of wrong polarity due to insufficient excitation to pull the rotor into proper polarity at reduced voltage.

If excitation be applied with the machine at rest, the magnetic circuit will be saturated, which will reduce the torque and increase the k.v.a. intake. Some additional surging will arise in the alternating-current line and pulsations will be caused in the direct-current line. After the motor has started, a counter-torque will be developed due to excitation and, under some conditions, this torque may prevent acceleration. If the field

excitation be applied before the motor has attained approximately 90 per cent of synchronous speed, the motor will not pull into synchronism and will probably slow down and run at reduced speed, taking a heavy fluctuating current.

During the starting operation it is desirable to know when the motor approaches or attains synchronous speed. This is indicated by a field ammeter of the permanent magnet type which should always be included in the control equipment. While the motor speed is well below synchronism the needle will vibrate due to the rapid alternations of the current in the short-circuited field circuit. As the slip decreases, the rapidity of the pulsations decreases and the deflections increase. When the motor pulls into synchronism the ammeter needle falls to zero. If direct-current excitation is applied before the motor pulls into step, the action is similar except that the needle does not return to zero but becomes stationary and indicates the amount of exciting current applied.

There are also pulsations in the stator current while the motor is running below synchronism, these being more distinct as the slip decreases. These pulsations are due to the variation of reactance with differing relative positions of the rotor pole pieces with respect to the stator poles. The stator current falls off markedly when the motor pulls into step. However, the field circuit pulsations give the most distinct indication of synchronous condition.

The sequence of operations, when starting and pulling into synchronism on reduced voltage, may be summarized as follows:

1. See that field switch is closed in position to short-circuit the fields through the proper resistance.
2. Close the switch to connect the motor to starting voltage.
3. When the motor has accelerated to synchronism or nearly so, as indicated by the field ammeter, build up the exciter voltage, apply excitation and adjust to proper value. The motor should then pull into step.
4. Transfer quickly from starting to running voltage.
5. Adjust field rheostat to running position.

Synchronizing on Full Voltage.—If the starting load is heavy, the motor may not be able to accelerate, with reduced voltage, sufficiently close to synchronous speed to enable it to pull into step. It is therefore common practice, particularly in starting heavy loads, to connect the motor first to reduced voltage and then to transfer to full voltage before applying excitation. The excitation should be applied immediately after the transfer to full voltage as the motor approaches synchronous speed. This method is simple and affords high pull-in torque. The current taken by the motor, operating as an induction motor on full voltage under load, may not always be permissible. Even though the motor can be brought nearly to synchronous speed while on reduced voltage, there will be a heavy rush of current when full voltage is applied, due to the high magnetizing current taken. There is also a possibility that, when excitation is applied, the relative positions of rotor and stator poles may be such that the rotor field momentarily bucks the stator field (until the rotor slips a pole). Under this condition a heavy current inrush will take place similar to that which occurs when two generators are thrown together out of phase.

Starting on Full Voltage.—It was shown in Fig. 70 that low-speed synchronous motors have relatively high impedance so that, if connected directly to full voltage in starting, the current inrush will not be prohibitive, no greater, in fact, than the current inrush to a high-speed motor with reduced voltage. Thus it is feasible to accelerate motors of this class on full voltage, applying excitation when full speed is approached. This method has the advantage of extreme simplicity and eliminates the transfer interruption and peak.

Automatic Starting.—Automatic controllers have been recently developed which will cause the various steps in the starting operation to be performed in sequence. The main circuits are handled by magnetic contactors. These may respond to suitable current-limiting or sequence relays in the motor circuits or a pilot motor, driving a master switch, may be used, giving time element starting. Protective devices are installed to prevent mishap should the motor fail to accelerate and pull into synchronism properly.

Variable Frequency Starting.—In a few instances, synchronous motors are started by applying variable frequency supplied from a special motor-generator set. Good torques can be obtained in this manner, if the generator and motor have low synchronous impedance and there is little reactance in the connecting lines. The principal advantage lies in the fact that the starting current peak may be minimized as the demand on the main system is energy current only.

Use of Magnetic Clutch.—Where pull-in torques in excess of full-load torques are to be handled or where it is desirable to minimize starting current peaks, the practice is often followed to start the motor without load and to apply the load through a clutch or otherwise. In the case of pumps, fans and air compressors, valves, dampers, or by-passes may be provided to minimize the starting requirement. Where clutches are used, they are usually of the magnetic type.

Efficiency.—The synchronous motor is an excellent machine from the standpoint of efficiency. It has a sustained high efficiency over a rather wide range of loads as indicated in Fig. 72. It ordinarily excels the induction motor in this respect, the difference being particularly marked in the case of low-speed machines. This characteristic is of especial advantage as referred to large, steadily loaded equipments such as fans and pumps. In Fig. 73 are shown the full-load efficiencies of a line of synchronous motors when operated at 100 per cent power factor. Figure 74 shows similar data for motors operated at 80 per cent leading power factor.

Stability.—The modern synchronous motor is quite satisfactory in the matter of stability. As previously stated, it has a pull-out torque of 150 to 300 per cent normal. It maintains its speed until this point is reached. The motor is able to follow ordinary changes in frequency and will carry a moderate load with a frequency as much as 20 per cent below normal. Hunting due to frequency changes is not ordinarily troublesome but may occasionally arise from combinations resulting from variations in angular velocity of synchronous apparatus on a system. The natural period of high-speed synchronous motors is much higher than the forced frequency of the system, so that hunting difficulties are improbable. Difficulty due to hunting

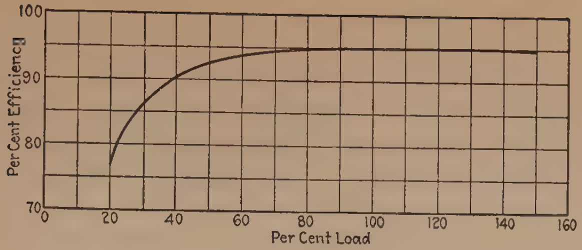
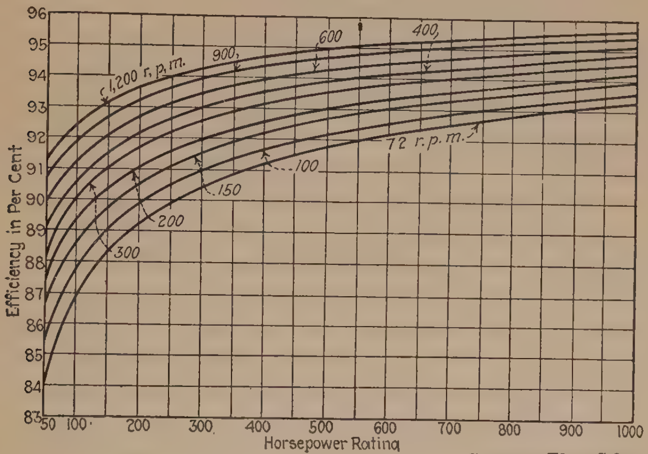


FIG. 72.—Efficiency-load curve of 250-H.P. 720 r.p.m. 60-Cycle synchronous motor.



Courtesy, Theo. Schou.

FIG. 73.—Full-load efficiency curves of synchronous motors operating at 100 per cent power factor.

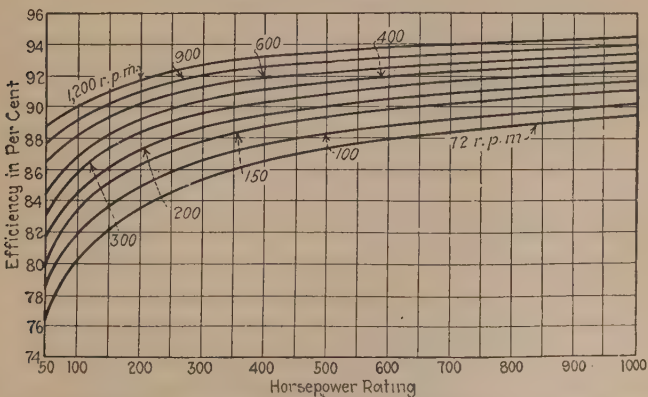


FIG. 74.—Full-load efficiency curves of synchronous motors operating at 80 per cent power factor.

is more likely to arise on systems supplied from steam- or gas-engine-driven generators than on systems supplied from steam-turbine-driven generators or water-wheel-driven generators. On a system subject to frequency variation due to irregular angular velocity of prime movers, some idle currents circulate between the generators and motors even though serious hunting does not occur. The cage-winding on a synchronous motor ordinarily damps out any material tendency to hunting.

Use of Flywheels.—Synchronous motors driving reciprocating machines, such as air compressors, have irregular loads imposed upon them. This irregularity of load tends to cause a variation in angular velocity. It also causes the motor to draw a pulsating current from the system. In such cases, flywheels are often provided to store energy during one part of the revolution and to deliver it during another part. The rotor of a synchronous motor is subject to swings behind and ahead of its normal position with changes of load. An increase in load causes the rotor to fall back, with reference to uniform rotation, until the increased torque developed balances the increased demand. A decrease in load causes an opposite effect. Due to the fact that the rotor and the revolving members connected thereto have appreciable inertia, when the rotor falls back it oversteps the mark and passes the position of balanced torques. The excess torque then developed by the motor causes the rotor to accelerate ahead of uniform rotation to overtake the position of balanced torques. Again the inertia comes into play and causes the rotor to accelerate too far. This cycle is repeated and the rotor oscillates ahead and behind uniform rotation with swings of decreasing amplitude. This oscillation has a natural frequency due to the inertia of the rotor and the strength of the torque impulses just as a pendulum has a natural frequency due to its mass and the force of gravity. If a pendulum be subjected to a force periodically applied in the right direction, its swings will increase in magnitude. Similarly, if a synchronous motor drive a cyclic load having any impulses of a frequency corresponding to the natural frequency of oscillation above described, its oscillations will increase in magnitude. Since these oscillations involve changes in rotor position they cause variations in current intake

from the power system. It is necessary to prevent the natural frequency of the rotor and any "forced" frequency due to the load from coinciding. The natural frequency changes somewhat with the excitation of the motor and depends also upon its synchronous impedance. The natural frequency may be changed by varying the inertia of the rotating member, usually by proper design of the flywheel. The presence of the squirrel-cage winding assists materially in damping the oscillations above mentioned. The flywheel is often proportioned to limit the angular deviation from uniform rotation to an amount not to exceed $3\frac{1}{2}$ electrical deg. The more recent practice is to limit the angular deviation to such an amount as will restrict the current pulsation to 60 per cent of full-load current. In connection with drives of this nature, the cooperation of the motor builder and machine builder is necessary to insure that the conditions above outlined are properly met.

The extra ~~weight~~ mass of a large flywheel increases the starting torque required to some extent. Indirectly it affects decidedly the pull-in torque. As a large flywheel may have too much inertia to be pulled into step from say 95 per cent speed, it may be necessary to reach perhaps 97 or 98 per cent speed by induction-motor action. It is much more difficult to obtain a high pull-in torque at 97 per cent speed because the induction-motor torque is nearly proportional to the slip and falls off decidedly as synchronism is approached. If the cage resistance be high, it may not be possible to reach 97 per cent speed by induction-motor action with any appreciable load on the motor.

Applicability.—The greatest advantage of the synchronous motor is its high power factor and its value for power factor correction. Its constant and maintained speed is sometimes an important benefit. The high and well-maintained efficiency is advantageous. The synchronous motor is well adapted for use on high-voltage lines as its stator can be built with fewer and larger slots than are used for an induction motor, and therefore the windings are easier to insulate. The rotor carries low-voltage windings only and is of rugged construction. The motor has a relatively wide air gap. In the larger sizes and at lower speeds the synchronous motor may be cheaper than the

equivalent induction motor. The synchronous motor has a strong tendency to maintain constant voltage without use of a regulator as a drop in line voltage causes the motor to draw leading current while a rise in voltage causes it to draw lagging current. This current, drawn through the reactances of the line and transformers, raises the voltage if the current is leading and lowers it if the current is lagging. If desired, a voltage regulator may be supplied and arranged to cause the motor to maintain constant voltage within the limits of its capacity. The synchronous motor also tends to balance the voltages in the different phases of an unbalanced system. This is brought about through the more marked influence of leading current in the low phase.

The synchronous motor has a number of inherent disadvantages. Among the foremost of these is the natural deficiency in pull-in torque and the heavy, lagging current taken in starting. The machine is less simple than the induction motor and requires perhaps a little higher grade attention. As the speed cannot be varied, this motor is suited to constant speed drives alone. It requires an exciter or excitation from a separate source. The control equipment is a little more complex. Notably in the smaller sizes and at higher speeds the cost is relatively high. Collector rings are required, but they give little trouble indeed. When installing motors of this type, cognizance must be taken of the fact that they increase the amount of synchronous apparatus connected to a system and thus influence the required rupturing capacity of switching equipment. In case of interruption of power, unless of very short duration, the motor is liable to drop back sufficiently to fall out of step.

Dynamic Braking.—The synchronous motor may be adapted for dynamic braking. This is accomplished by disconnecting the stator winding from the supply system and short-circuiting it through suitable resistance, at the same time applying reduced excitation. A braking effort exceeding full-load torque can be developed in this manner. This feature is of decided advantage in certain instances, as for some rubber mill drives.

Voltage.—In applying synchronous motors it is desirable

that care be exercised so that the voltage rating of the machine corresponds with the system voltage at the point of application. If a 2,200-volt motor be subjected to 2,400 volts, for instance, it is evident that considerable excess excitation will be required to obtain the desired power factor.

Range of Sizes.—Synchronous motors are now available and in common use in sizes ranging from about 50 to 2,000 hp. and for speeds from 60 to 3,600 r.p.m. The great majority of motors installed range in size from 100 to 500 hp. and in speed from about 90 to 900 r.p.m. As previously indicated, the use of the synchronous motor is not ordinarily feasible in the smaller sizes and it compares particularly favorably with other motor types at the lower speeds. Induction motors have especially low power factor and relatively low efficiency when built with a large number of poles to operate at slow speed, so that the advantages of the synchronous motor are then especially pronounced. The lower speed ratings mentioned apply to motors of large size. High-speed ratings are not common because the high-speed synchronous motor offers relatively small advantage over the equivalent induction motor except for leading power factor operation and also because difficulties involved in constructing rotors with definite pole pieces in the limited space and for high speeds add to the cost of such designs.

Applications.—Synchronous motors are very commonly used in motor-generator and frequency-converter sets. A set comprising two synchronous motors, such as a frequency-converter set, is reversible in that either unit may serve as a motor or generator, as required. Thus they form an excellent link between two systems having varying power requirements. The principle of reversibility is also utilized in a few cases of dual drive of power plant auxiliaries in which case the motor may function as a generator, when required, being driven by the steam unit and supplying power for other auxiliaries. Synchronous motors are now regularly applied for driving fans and blowers, centrifugal pumps, air and ammonia compressors, tube mills, flour mills, rubber mills, pulp grinders and jordans and for other similar applications where constant speed, continuous operation and infrequent and moderate starting

requirements prevail. They are also finding some application as a sort of electrical gearing for maintenance of relative speeds of different machines, as in sectionalized paper machine drive.

Synchronous Induction Motor.—The so-called "synchronous induction motor" is similar in all respects to a standard squirrel-cage induction motor except that the rotor is cut away to give a definite pole construction. This motor starts as an induction motor and operates as a synchronous motor without direct-current excitation, the excitation being taken from the alternating-current system. It is thus entirely similar to the standard synchronous motor which pulls into step before excitation is applied. Motors of this type will not carry a heavy load. A notable application of this type of motor is in connection with mechanical rectifiers as used for electrical precipitation. These motors are of about 5 hp. rating and the load is light but synchronous speed is essential.

"Super-synchronous Motor."—An interesting variation of the synchronous motor is the so-called "super-synchronous" motor recently developed by the General Electric Co. The name is somewhat misleading as the motor does not exceed synchronous speed. This motor is similar to a standard revolving field synchronous motor except that the stator core and windings are arranged to revolve and are connected through three slip rings on the shaft. In normal operation this motor is similar to any other except that its stator is held against rotation by a brake band applied at its periphery. In starting, the rotor, carrying the field poles, is held stationary by the load. The brake band is released and the stator revolves and attains synchronous speed. The brake band is then gradually applied, manually, and the rotor thus caused to accelerate. The action is similar to that obtained with a standard synchronous motor started light and having its load applied by a mechanical clutch after the motor has attained speed.

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CHAPTER VIII

SINGLE-PHASE MOTORS

SINGLE-PHASE SERIES MOTORS

If the two line terminals of a direct-current series motor be interchanged, the motor continues to rotate in the same direction, being indifferent to the polarity of its terminals. It follows theoretically that the motor should be operative upon alternating current. Since the armature and field are in series, the reversals of armature current and field current are simultaneous and the direction of the torque remains unchanged. A number of modifications are necessary, however, to adapt the series motor for alternating-current operation. The rapid reversals of current cause equally rapid reversals of main flux. Such magnetic changes will cause excessive eddy currents in a solid iron magnetic circuit. It is necessary, then, to laminate all portions of the magnetic circuits of motors of this type in order to limit the iron losses. The field windings of a series motor necessarily have considerable inductance. This inductance lowers the power factor and causes the voltage at the armature terminals to drop off quite rapidly with increase of load, affecting the speed regulation and the maximum torque. The self-induction or choking action of the fields is proportional to the field flux and to the square of the number of turns in the field winding. It is desirable that the inductance be maintained as low as possible. This is done partially by using a low field flux. Also, for the sake of good commutation, it is desirable to reduce the field flux which induces currents in the coils short-circuited by the brushes. Since the torque is proportional to the field strength a low flux means the use of a large number of armature conductors to develop the required torque. A large number of armature conductors implies an armature

with comparatively strong magnetizing influence, which would cause great distortion of a weak field. This feature is overcome by neutralization, later explained. The field inductance is reduced by restricting the number of field turns as well as the field flux. Low flux density, small total flux, short air gap, a large number of poles with short magnetic circuits and high quality iron all contribute to reduce the field turns required. Since inductance is proportional to frequency, it follows that motors of this type are better suited to low than to high frequencies.

Simple Series Motor.—Figure 75 shows diagrammatically the connections of an alternating-current series conduction

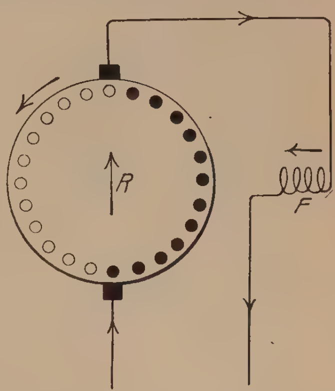

FIG. 75.

Simple single-phase series motor. At the instant shown:

1. Supply voltage is past maximum, diminishing.
2. Field current in F is maximum.
3. Motor flux F is maximum.
4. Armature current is maximum (same as field current).
5. Armature reaction flux R is maximum.
6. Torque, due to interaction of items 3 and 4, is maximum. Note that torque varies in value during each cycle.

Note that conductors under brushes have a voltage induced in them due to transformer action from F and a voltage generated in them due to cutting R.

motor. The armature conductors are represented by dots and circles which show the instantaneous direction of current flow. The outer ring represents the commutator. It is assumed that the leads from the armature coils come out to commutator bars directly in front of them. The field coils set up a reversing motor flux F, in the direction of the arrow. The armature conductors constitute, in effect, a magnetizing coil which sets up an armature field in the direction R. Because of the necessity of maintaining these two fields a series motor of this type has a low power factor. The motor flux F and the armature

reaction flux R are in phase with each other since they are both caused by the same current. The motor flux and the armature current react upon each other to produce torque. The armature current and the motor flux are practically in phase and the torque is independent of the power factor.

The flow of armature current represented by the dots and circles in Fig. 75, is caused by the impressed voltage and opposed by the counter-voltage of rotation, just as in a direct-current motor. It should be noted that, in addition, the reversing flux F links the armature coils short-circuited by the brushes and thus, through transformer action, sets up a voltage in them. The resulting short-circuit current may be quite heavy if the motor flux is strong. This circuit is interrupted as the short-circuited coils pass out from under the brushes, giving rise to serious sparking. The induced voltage is made as low as possible by using a comparatively weak field, also by restricting the number of turns between commutator bars. This necessitates a large number of armature coils, each having a few turns, in many cases a single turn. Since the induced voltage depends upon the frequency, a low frequency is favorable to good commutation. The short-circuit current flow, with a given inducing flux, depends directly upon the resistance of the local circuit comprising an armature coil, two commutator bars and a brush. The resistance of this circuit is often made purposely high by the insertion of preventive leads of high resistance between armature coil and commutator bars as shown in Fig. 76. It will be seen that only the resistance leads connected to the bars momentarily under the brushes, carry working current; at all other points around the armature the working

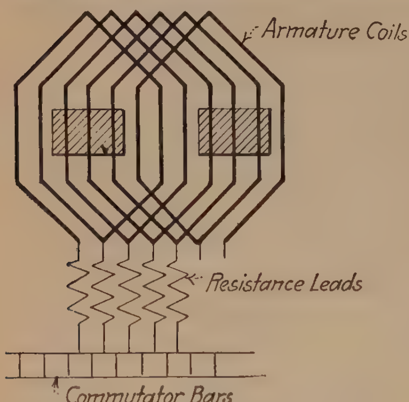

Fig. 76.—Commuted windings with resistance leads.

current passes through the armature coils only. Reduction of short-circuit current is thus secured with little loss in efficiency; in fact, the efficiency may be raised through reduction of the short-circuit currents with their attendant losses. Preventive leads are effective and are considerably used, particularly in railway motors. As an added complication, they are subject to objection.

Machines of this type have a series characteristic, the field strength varying with the load and the speed varying approxi-

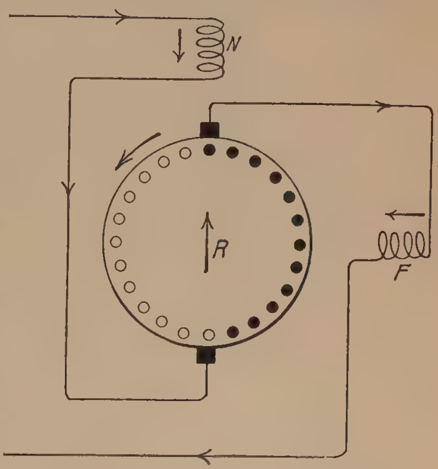

FIG. 77.

Neutralized single-phase series motor.

At the instant shown:

1. Supply voltage is past maximum diminishing.
2. Field current in F is maximum.
3. Motor flux in F is maximum.
4. Armature current is maximum (same as field current).
5. Armature reaction magnetizing force R is maximum.
6. Current in N is maximum (same as in F and armature).
7. Magnetizing force of N, opposed to R, is maximum.
8. Torque, due to interaction of items 3 and 4 is maximum.

Conductors under brushes have a voltage induced in them due to transformer action from F but, if R and N are equal, there is no cross flux, hence no voltage generated in these coils.

mately inversely as the load. The starting torque is high. The power factor decreases with increase of load but increases with rising speed and is particularly low at starting. The direction of rotation may be reversed by reversing the armature with respect to the field or vice versa. The stator may be built with projecting poles and coil windings or the poles may be formed within a smooth bore by distributed windings. Simple series alternating-current motors are built only in fractional horsepower sizes operating at high speeds.

Neutralized Series Motor.—In the simple series motor above described, the armature reaction flux R performs no useful work but distorts seriously the motor field and is detrimental to commutation. The lagging voltage component required to maintain this flux lowers the power factor. In the motor shown in Fig. 78, a neutralizing winding, sometimes called a compensating winding, has been added. This winding has a magnetizing influence N approximately equal and opposed to that of the armature and thus neutralizes the armature field R. The neutralizing winding is most effective if it

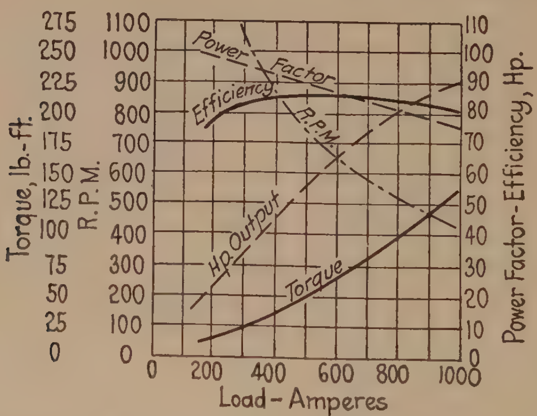

FIG. 78.—Operating characteristics of a neutralized single-phase series motor for railway service.

is distributed over the stator bore in a way similar to the distribution of the armature winding over the armature. Each element of armature magnetizing influence is thus neutralized and all distortion of the motor field prevented. Figure 78 shows the characteristic curves for a neutralized series railway motor. These curves are quite similar to those of the direct-current series motor. The speed curve does not flatten out and approach a constant value under heavy loads as is the case in a direct-current series motor. This is because of the low flux density used and the consequent lack of saturation influence. The power factor of a motor of this type is materially higher than that of a simple series motor. The power factor rises

with rising speed and decreases with increase of load. Commutation is better in the neutralized type of machine. In other respects the performance is similar to that of the simple series motor. This general type of motor is used largely for alternating-current traction work and in some fractional horsepower designs.

Inductively Neutralized Series Motor.—It is not necessary that the neutralizing winding be in conductive relation to the armature. The motor may be arranged as in Fig. 79. Here the neutralizing coils are short-circuited windings. The armature and the short-circuited neutralizing winding behave like a short-circuited transformer in which the armature is the primary and the neutralizing winding the secondary. The transformer flux or flux of mutual induction is determined by the vectorial difference between armature and neutralizing winding ampere-turns. The flux in the brush axis cannot be entirely neutralized in the inductively neutralized motor for

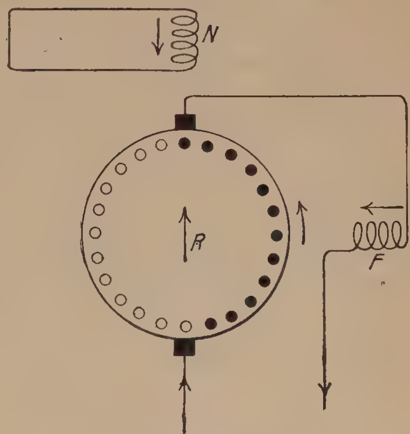

FIG. 79.

Inductively neutralized single-phase series motor.

At the instant shown:

1. Supply voltage is past maximum and diminishing.
2. Field current in F is maximum.
3. Motor flux in F is maximum.
4. Armature current is maximum (same as field current).
5. Armature reaction magnetizing force R is maximum.
6. Magnetizing force of N is at its maximum and is opposed to R (on the assumption of a neutralizing winding without ohmic resistance).
7. The resultant magnetization and flux in the brush axis is due to the difference between magnetizing forces R and N and is maximum.
8. The voltage induced in the neutralizing winding N by the above flux is passing through zero.
9. Torque is due to items 3 and 4 and is maximum.

the reason that a small inducing flux is necessary to the action of a short-circuited neutralizing winding. The magnitude of the inducing flux is determined by the resistance and reactance of the short-circuited neutralizing winding. These usually being very low, the inducing flux required is very small indeed. The performance of this type of motor is thus practically the same as that of the conductively neutralized motor shown in Fig. 77. The inducing flux is usually so small as to have no material influence on commutation. Inductive neutralization has a number of advantages. It automatically assumes a value to closely counterbalance the armature influence, a condition requiring exact design in the conductively neutralized motor. If the neutralizing winding is arranged by short-circuiting each turn instead of short-circuiting the winding as a whole, the current in the individual turns will automatically attain the proper values to counterbalance the armature influence opposite them and will thus distribute the neutralizing influence exactly as required. Another marked advantage is the very low potential of the short-circuited neutralizing winding to ground, making insulation simple and trouble unlikely.

Neutralizing windings, in general, may be placed upon projecting pole pieces, or may be located in slots in a smooth-bore stator but always in such a way that their magnetizing influence is 90 magnetic degrees displaced from that of the main poles. They bear a relation similar to that of the interpole to the main pole in the direct-current motor. The interpole, however, neutralizes armature magnetizing influence over a narrow zone only, while a properly designed neutralizing winding neutralizes all armature magnetization and entirely prevents main field distortion. The neutralizing winding is thus identical with the "compensating" windings discussed in Chap. IV in connection with direct-current motors.

Neutralized Series Motor with Rotor Excitation.—The machine shown in Fig. 79 can also be operated with a single winding on the stator, whether the latter has polar projections or not. To this end it is only necessary to displace the brush line from the axis of the single-stator winding as shown in Fig. 80. The current conducted through the armature produces

a magnetization one component R of which is coaxial with the stator winding N and due to the rotor conductors within the angles, 180-2α deg. on each side of the axis of N, while the other Fr is perpendicular to said axis and due to the remaining rotor conductors. The stator winding N is connected to oppose R and can readily be dimensioned to equal it. It acts as a neutralizing winding. The flux Fr does duty as the motor

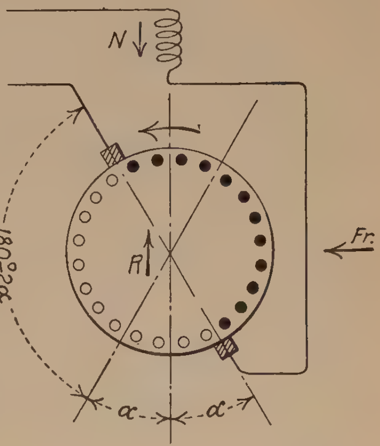

FIG. 80.

Neutralized single-phase series motor with rotor excitation.

At the instant shown:

1. Supply voltage is past maximum and diminishing.
2. Current in N is maximum.
3. Vertical magnetizing force due to N is maximum.
4. Armature current is maximum (same as N).
5. Field Fr, due to armature current in top and bottom conductors in arcs 2 (2α) is maximum.
6. Armature reaction magnetizing force R, due to armature current in conductors in arcs 2 (180–2α) is maximum.
7. R is opposed and may be neutralized by N.
8. Torque is due to interaction of 4 and 5 and is maximum.

field, being responsible for the torque of the machine in conjunction with those rotor ampere-turns which are neutralized by N. The rotor winding of this motor functions both as armature and as field or exciting winding.

SINGLE-PHASE SERIES INDUCTION MOTORS

Self-excited Series Induction Motor with Rotor Excitation. (*Repulsion Motor.*)—This class of motor differs from the foregoing series motors in that here energy is conveyed to the armature circuit by induction instead of by conduction. Figure 81 diagrammatically illustrates the best known form of such a machine, usually referred to as a repulsion motor.

The action and theory of this motor are most easily understood when it is pointed out that the conduction machine shown in Fig. 80 can be converted into the induction type illustrated in Fig. 81, by simply short-circuiting the brushes of the former. The winding S, in Fig. 81, which corresponds to N of Fig. 80,

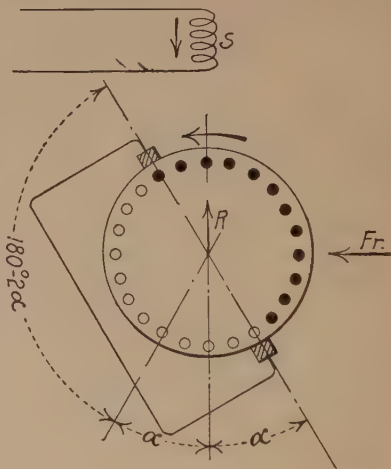

FIG. 81.

Self-excited single-phase series induction motor with rotor excitation (repulsion motor).

At the instant shown and for an ideal motor:

1. Supply voltage is maximum.
2. Magnetizing current in S is passing through zero.
3. Vertical inducing flux S is zero.
4. Voltage induced in armature by inducing flux is maximum.
5. Armature current is maximum.
6. Motor field Fr, due to armature current in conductors in arcs 2 (2α) is maximum.
7. Armature reaction magnetizing force R, due to armature current in conductors in arcs 2 ($180-2\alpha$) is maximum.
8. R is neutralized by S, causing the load current intake from the supply. Load current in S is maximum.
9. Voltage generated in armature due to cutting Fr is maximum, is opposed to item 4 and is enough less than item 4 to permit required load current to flow.
10. Voltage generated in armature due to cutting inducing flux S is passing through zero. This voltage improves the power factor of the motor.
11. Torque is produced mainly by interaction of items 5 and 6. Torque is maximum.
12. This motor has a series characteristic because the motor field Fr varies with the armature current.

is the only part of the machine directly connected to the source and now becomes the main inducing winding.

The magnetizing current in the inducing winding S sets up a vertical flux which, by transformer action, induces current in the rotor conductors as indicated by the dots and circles. This current, being induced, is, in normal operation, practically in

quadrature with the vertical transformer flux S. The rotor conductors within the two arcs (180–2α) deg. are armature conductors and have a vertical magnetizing influence which is opposed by the coil S. The current in these conductors is energy current, drawn from the primary by induction and reflecting upon the primary circuit the influence of mechanical load. The rotor conductors at top and bottom within the two arcs 2α deg. are field conductors, have a horizontal magnetizing influence and set up the motor field Fr. This field, set up by the energy current in the armature, is in phase with it. Since the rotor current is in quadrature with the transformer flux S and in phase with the motor flux Fr, it follows that these two fields are in time quadrature. The torque of the motor is produced by interaction of the energy current in the rotor conductors 2(180–2α) and the motor field Fr set up by the remaining rotor conductors. The rotor conductors within the two arcs (180–2α) deg., due to cutting the motor field Fr, have generated within them a voltage which is in time phase with Fr, and thus in time quadrature with the vertical transformer flux S. This voltage is in phase with and in opposition to the voltage induced in these conductors by the transformer flux. The speed so adjusts itself that the difference between these two voltages is just sufficient to pass the required load current.

The rotor conductors within the two arcs 2α, due to cutting the transformer field S, have generated within them a voltage which is in time phase with S. This voltage is in time quadrature with the voltage induced in the rotor conductors 2(180–2α) by the transformer flux S. This voltage, generated in the field or exciting rotor conductors $2(2\alpha)$, decreases the impedance of the rotor and thus improves the power factor of the machine. This is an outstanding characteristic of this type of motor.

It will be seen that this machine comprises essentially a single stator winding and a rotor carrying short-circuited brushes located at an angle with respect to the main field. In its action it is a transformer, the secondary being movable and the secondary coils being short-circuited in a line inclined at an angle to the primary coils. The secondary current,

flowing in portions of the rotor conductors, sets up the motor field and the same current, flowing in the balance of the rotor conductors, reacts upon that field to produce torque.

If the brushes were located in the line of the inducing winding, there would be no flux component *Fr*. The flux would all be vertical transformer flux. Current would be induced in the rotor conductors but there would be no torque since the current distribution in the rotor conductors would be coaxial with the only existing flux. If the brushes were located 90 deg. from the line of the inducing windings, there would be no current in the rotor conductors since, with respect to the brush short-circuit, the voltages induced in half the rotor conductors would oppose the voltages induced in the other half. The first position of the brushes above mentioned is commonly called the live neutral position, the second is called the dead neutral position. If the brushes be shifted slightly from the live neutral position the rotor will rotate in the direction of the shift or displacement. It is evident that the angular position of the brushes is necessary to the action of the machine. The amount of angularity has considerable influence upon the action since it varies the relative number of field-magnetizing conductors and energy or armature conductors on the rotor. Up to a certain point, the greater the angular shift from the live neutral, the greater is the torque at rest but the lower the speed for a given load. A small angularity gives the greatest pull-out torque, a large angularity gives the greatest starting torque. An intermediate compromise position is generally used. The behavior of a machine of this type is sensitive to changes in the position of the brushes. The motor above described is known as a simple repulsion motor. It is in reality a form of the series induction motor in which the exciting ampere-turns are located on the rotor and the exciting current is generated in the motor itself.

Series Induction Motor with Rotor Excitation. (*Compensated Repulsion Motor.*)—Another type of the series induction motor is shown in Fig. 82. Here the armature or working brushes are located on the live neutral, in line with the inducing winding *S*. This winding sets up a transformer flux which induces the energy current in the rotor. Additional brushes, called ex-

citing brushes, are located on the dead neutral, 90 deg. from the working brushes. These brushes are in series with the inducing winding and carry the line current. The instantaneous direction of the flow of current conducted into the rotor through the exciting brushes is shown by the external circles

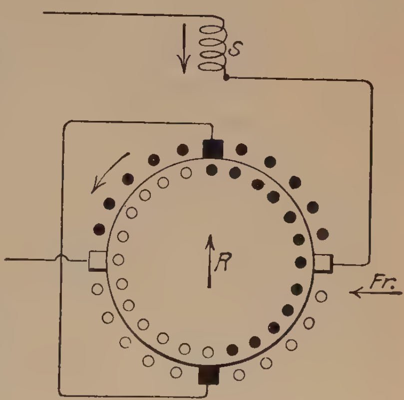

FIG. 82.

Single-phase series induction motor with rotor excitation (compensated repulsion motor).

At the instant shown and for an ideal motor:

1. Supply voltage is maximum.
2. Magnetizing current in S is passing through zero.
3. Vertical or transformer flux is passing through zero.
4. Voltage induced in rotor by transformer flux is maximum.
5. Load current in rotor set up by above voltage, is maximum. Indicated by inner dots and circles.
6. Magnetizing force R, due to load current in rotor, is maximum.
7. Load current is taken by S to create a magnetizing force to neutralize R. This current is maximum.
8. The primary load current (item 7) flowing through the rotor is indicated by the outer dots and circles. This sets up the field Fr, which is maximum.
9. Torque is produced by coöperation of 5 and 8.
10. A counter-voltage is generated in the rotor conductors due to cutting the field Fr. This appears at the vertical brushes, is a maximum and opposes item 4. The speed is such that this voltage is less than item 4.
11. A voltage generated due to cutting the vertical or transformer flux, is zero at this instant. This voltage appears at the horizontal brushes and is such as to improve the power factor of the motor.

and dots. The instantaneous direction of flow of energy current induced by the transformer flux is shown by the internal circles and dots. There is, in reality, but a single rotor winding, the double set of circles and dots being used merely to distinguish the individual action of the superimposed currents.

It will be seen that the current from the exciting brushes

gives to the rotor a magnetizing influence and sets up a field along the line *Fr*. This constitutes the motor field of the motor. A voltage is generated by rotation of the rotor conductors through the transformer flux. This voltage appears at the exciting brushes and its phase is such as to improve the power factor of the machine. The action is quite similar to that described in connection with the motor shown in Fig. 81, with the difference, however, that the self-compensating voltage of Fig. 81 is injected into the secondary while in this case it is injected into the primary of the motor. The motor here described is commonly called a compensated repulsion motor. It has a number of varied forms, only a few of which find commercial application.

The general characteristics of series induction or repulsion motors are identical with those of the series conduction motor, the speed varying materially with load changes. The speed regulation, maximum torque and starting torque values can be materially influenced by slight movement of the brushes. In some cases rotation is reversed by movement of the brushes from one side of the live neutral to a corresponding position on the other side of the live neutral. In others this result is secured by a simple change in connections. Rotation is in the direction of the brush shift. Series induction motors exert a good starting torque but have low power factor at starting and are likely to spark when starting. They are also usually noisy while accelerating. The self-excited series induction motor has an advantage in the isolated rotor arrangement, inasmuch as its potential above ground is low and its insulation subject to little strain. The series induction motor types above shown are not used extensively. A number of motors are designed to act as series induction motors while starting and to run as shunt induction motors.

Commutation.—In a direct-current motor the brushes are always placed in the position about midway between the main poles where the commuted coils cut little or no flux. In the single-phase motors above described the coils undergoing commutation are subject to the influence of one or more fluxes.

Consider the commutating conditions in a machine of the type shown in Fig. 81. There is a reactance voltage in the

commuted coils, identical in nature with the reactance voltage in the commuted coils of a direct-current machine. In addition there must be considered the voltage generated by rotation in the transformer flux and one generated by rotation in the motor flux *Fr*, also the voltage induced by the transformer flux and that induced by the motor flux. The generated voltages are in phase with their respective fluxes. The induced voltages lag 90 deg. behind their respective fluxes. Near synchronism the transformer and motor fluxes are practically of the same magnitude and, when the power factor is near unity, they are practically in quadrature. Under these conditions the voltage induced by the transformer flux is equaled and opposed by the voltage generated by the motor flux and that generated by the transformer flux is equaled and opposed by the one induced by the motor flux. The commutating conditions then depend solely on the magnitude of the reactance voltage of the commuted coil, as in a direct-current motor. Entirely satisfactory commutation is then readily obtainable. For speeds materially below the synchronous and for power factors other than unity the commutation conditions rapidly grow poorer. The generated voltages vary with the speed and the magnitude of the flux whereas the induced voltages are independent of the speed. The opposition of induced and generated voltages is incomplete and resultant voltages exist in the commuted coils. The commutating conditions are particularly poor at starting because of the total absence of generated voltages at standstill.

The conditions are similar in the coils short-circuited by the working and exciting brushes of the motor shown in Fig. 82. Such differences as exist favor the exciting brushes. At starting the induced voltage in their axis is small because the transformer flux is then small. In normal operation these brushes also carry less current than the working brushes and the reactance voltage in the coils they control is consequently smaller.

The conditions are somewhat different in the first-mentioned types of series motors in which the armature current is introduced conductively. The generated and induced voltages occur in the coils short-circuited by the brushes, as in the series induction motor. In the series induction motor the motor

flux and the transformer flux are, at times, in time quadrature so that the induced voltage and generated voltage in the short-circuited coils are in opposition. In the series conduction motor the motor flux and the armature reaction flux are always in time phase with one another so that the induced voltage and generated voltage in the short-circuited coils are in quadrature. The resultant short-circuit current then depends upon the vectorial sum of these voltages and on the reactance voltage. In the neutralized series motor the armature reaction flux is very small and its influence on the short-circuit currents is negligible. These currents then depend mainly upon the reactance voltage and the motor field strength, being greater with heavier loads, at lower speeds and at starting. As previously explained, this induced short-circuit voltage is made as small as possible through the use of a weak motor field and few armature turns per coil and the short-circuit current is frequently further reduced by the use of preventive resistance leads.

SINGLE-PHASE SHUNT MOTORS

It is not feasible to build a separately excited alternating-current conduction motor paralleling the direct-current shunt type. The chief reasons may be briefly summarized. The armature of such a motor has much lower inductance than the field circuit so that the two currents differ considerably in phase. The armature current and the field flux are not in phase and the torque for a given input is low. Such a motor is heavy for its rating. Due to the high inductance of the field circuit, the power factor is low. Commutation is poor because of heavy induced short-circuit currents. Self-excited (rotor-excited) single-phase shunt conduction motors have, however, been built which are free from these drawbacks. The motors in common use for approximately constant speed duty are ramifications of the shunt induction motor, in which electric energy is conveyed to the rotor by induction rather than conduction. The discussion will therefore be confined to motors of this general type.

Self-excited Shunt Induction Motor. (*Single-phase Induction Motor.*)—The polyphase induction motor depends, for its action, upon a revolving magnetic field resulting from the proper arrangement in the bore of the inducing member, usually the stator, of coils receiving currents out of phase with each other. In a single-phase induction motor it is impossible, without the use of some phase-splitting device, to create a rotating field by any arrangement of stator coils, inasmuch as the current for all coils is obtained from a single phase. A standard polyphase induction motor will operate upon a single phase, however, if it is first caused to reach a nearly synchronous speed by some starting arrangement.

Production of Speed Field.—Let us consider the motor shown in Figs. 83*a* and *b*. This is identical with a two-phase squirrel-cage induction motor with one stator phase winding omitted. The field set up by the single-phase stator or inducing winding does not rotate but merely reverses, oscillating through a series of values. This field is set up by a magnetizing current in the stator winding. Let us assume that the rotor is revolved at synchronous speed. The rotor conductors, due to their motion across this field, which may be called the "transformer" or "inducing" field, have generated in them a voltage. This voltage is maximum when the inducing field is maximum. It is therefore in time phase with the inducing field. We will call this voltage, due to the cutting of the inducing field by the rotor conductors, the exciting voltage. Maximum exciting voltage is generated in the rotor conductors located on the axis of the inducing field. No exciting voltage is generated in the rotor conductors in the axis at right angles to that of the inducing field. The exciting voltage forces through the closed rotor circuits an exciting or magnetizing current which produces a magnetization at right angles to that of the inducing field. The instantaneous direction of exciting current flow is indicated by the dots and circles in Fig. 83*a*. The axis of the alternating magnetization produced by the exciting current in the rotor conductors of a single-phase induction motor is stationary in space, notwithstanding the rotation of the rotor, and is known as the "motor" or "speed" field. It is indicated in Figs. 83*a* and *b*, by *Fr*.

Phase Magnitude of Speed Field.—Since magnetizing current lags 90 deg. behind the voltage which forces it through the rotor conductors, the exciting current, and the flux due to it, reach a maximum when the exciting voltage is a quarter-cycle ahead at zero. The result, in the case of our motor, is that the speed field *Fr*, set up by the exciting current in the rotor conductors along an axis in space quadrature to the inducing field, is out of time phase 90 deg. with the inducing field *S*.

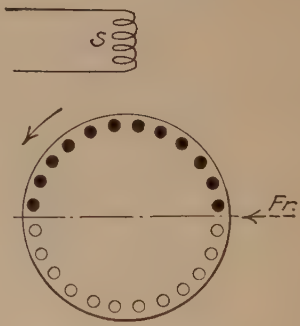

Fig. 83*a*.

Self- (rotor) excited single-phase shunt induction motor (single-phase induction motor), showing production of motor field *Fr*.

At the instant shown and for an ideal motor:

1. Supply voltage in *S* is maximum.
2. Magnetizing current in *S* is passing through zero.
3. Inducing (vertical) flux is passing through zero.
4. Exciting voltage, generated by cutting inducing flux, is passing through zero.
5. Exciting current, due to exciting voltage, a lagging magnetizing current, is maximum. (This current is indicated by dots and circles.)
6. Motor flux *Fr* is maximum.
7. Voltage induced by alternating flux *Fr*, opposing the exciting voltage, is passing through zero.

Magnetizing forces due to load current are shown solid.

Magnetizing forces due to other than load currents are shown dotted.

We thus have the inducing field and the speed field in space quadrature and time quadrature. This is exactly the flux condition set up by the two-phase inducing windings in the stator of a two-phase induction motor. The inducing field *S* and the speed field *Fr* in a single-phase shunt induction motor combine to produce a rotating field such as exists in a polyphase motor. When the motor is at rest, the rotor conductors do not cut any magnetic lines, so have no exciting voltage and current generated in them to set up a speed field. Therefore a motor of this type will not start without some special means. At any speed less than the synchronous, the rotor conductors

cut the flux of the inducing field less rapidly, hence the exciting voltage is less than that corresponding to synchronous speed. This leads to a lesser speed field. The resultant revolving field, which is uniform at synchronous speed, becomes elliptical at speeds below the synchronous. At standstill the inducing field alone exists and appears along the vertical axis.

Load Current and Production of Torque.—It has been shown that the exciting voltage is generated in the rotor conductors

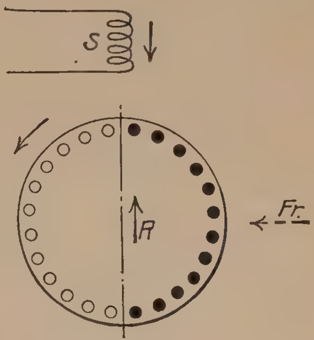

Fig. 83*b*.

Showing reflection of rotor load current demand to primary; showing also the production of torque.

At the instant shown (same as Fig. 83*a*):

1. Supply voltage in *S* is maximum.
2. Magnetizing current in *S* is passing through zero.
3. Vertical inducing flux is passing through zero.
4. Voltage induced in rotor by vertical inducing flux, is maximum.
5. Motor flux *Fr* is maximum, see Fig. 83*a*.
6. Voltage generated by cutting motor flux *Fr* is maximum. This voltage is opposed to item 4. Motor "slips" until item 6 is less than item 4 by an amount sufficient to pass load current sufficient to develop required torque.
7. Induced load current in rotor, due to margin of induced voltage over generated counter voltage, is maximum. (This current is indicated by dots and circles.)
8. Vertical magnetizing force *R*, due to load current in rotor, is maximum.
9. Line load current is taken in *S* to oppose and neutralize force *R*.
10. Torque is produced by co-operation of items 5 and 7 and is maximum.

by rotation of the latter in the vertical inducing or transformer field. This field has another influence on the rotor conductors which is quite independent of rotation. This field induces a voltage in the rotor conductors. This voltage is zero in the rotor conductors on the vertical axis and maximum in those on the horizontal axis. The current in the rotor conductors due to this induced voltage has a magnetizing influence along the vertical axis in line with the stator inducing winding. The

induced rotor voltage is the working voltage of the machine and corresponds to the voltage conductively impressed on the armature of a direct-current motor. The induced current in the vertical axis, above described, is the secondary load current. Its derivation is further indicated and explained in Fig. 84*b*.

When the rotor revolves, the rotor conductors cut the speed field as well as the transformer field and a second speed voltage is thereby generated. It appears along the vertical rotor axis and is opposed to the voltage induced along that axis. It is the counter-voltage of the motor. At synchronism, and on the assumption of an ideal motor, all rotor voltages are equal. The induced working voltage is exactly equaled and opposed by the generated counter-voltage in the vertical axis. The generated exciting voltage is exactly equaled and opposed by the voltage induced in the horizontal axis by the speed field. In practice, the speed will always be below the synchronous and sufficient voltage differences will occur to permit the flow of required exciting and load currents.

Torque is produced by the induced load current in the vertical axis in cooperation with the speed flux Fr in the horizontal axis. In normal operation this secondary load current is approximately in phase with the induced voltage and is thus also in phase with Fr since both the induced voltage and the speed field Fr differ 90 deg. in time phase with the vertical transformer flux.

Starting.—A common method of starting motors of this type is by means of a phase-splitting device, one form of which is shown diagrammatically in Fig. 84. The motor has windings arranged the same as in a three-phase motor. The rotor is of the squirrel-cage type. The phase-splitting is accomplished with the help of a resistance and a reactance. At starting the switch connects point 1 to 3 and 5 and point 2 to 4 and 6. In this connection the resistance is in parallel with the stator phase 10–11 or in series with the stator phase 9–11 while the reactance is in series with 10–11 and in parallel with 9–11. The line voltage is impressed directly on the stator phase 9–10 but the voltage impressed on the two other stator phases is modified as to phase and magnitude by the interposition of

said resistance and reactance. An approximate three-phase condition is thus obtained and a rotating field is set up in the motor, causing it to start. When it has attained nearly synchronous speed the starting device may be cut out, connecting switch points 1 and 2 with 7 and 8 respectively, and the motor will continue to operate as a single-phase machine. Two leads only will then be in use. Inasmuch as the starting torque developed through the use of a phase-splitting device is small, motors of this type are ordinarily built with the rotor revolving

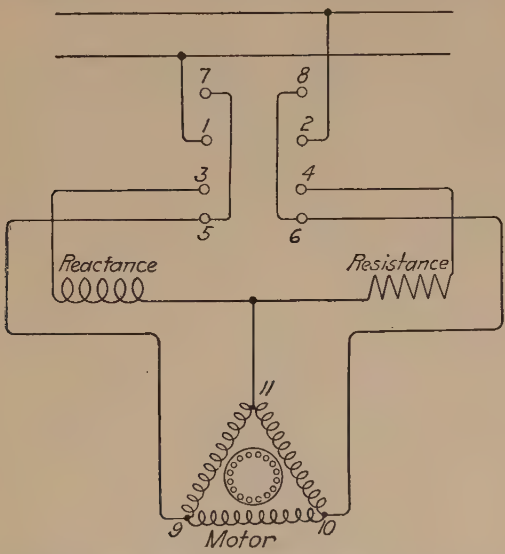

FIG. 84.—Diagram of split-phase motor with starting and running connections.

freely on the shaft and transmitting torque through a clutch. This clutch is so arranged as to become operative when the motor has reached a speed slightly below synchronism. In this manner the motor is enabled to start without load, and is not called upon to accelerate a load until a favorable torque condition has been attained. During the period of load acceleration there is a certain amount of slippage in the clutch. Motors of this type will accelerate against about 150 per cent full-load torque with a current input of about 250 per cent

full-load value. They will carry about 75 per cent overload before the clutch allows slippage. It should be noted that full-load current is higher in this motor than in one having better power factor, the horsepower ratings being the same.

Power Factor.—The revolving field in the single-phase induction motor is set up by the combined influence of the inducing field and the rotor's speed field. The magnetizing force required to set up the inducing field magnetism is equivalent to that of one phase in a two-phase motor. The magnetizing force required to set up the speed field is of like magnitude. The magnetizing current for the speed field must come originally from the single-phase stator winding connected to the line. This winding is responsible for two component fields similar to those set up by the two phases of a two-phase stator winding. The magnetizing current taken by this single phase is thus about twice that taken per phase by a two-phase motor. The high magnetizing current necessary in a single-phase induction motor causes the power factor of this type of machine to be comparatively low.

Maximum Torque.—The speed field in a single-phase motor is dependent directly upon the exciting voltage generated in the rotor. This generated voltage varies directly with the speed and the main inducing field. With a large slip and large stator current the speed field is materially reduced below its value at synchronous speed. Therefore, the resultant rotating field is elliptical in shape and its average strength is reduced. The maximum torque depends upon the strength and uniformity of the rotating field. It is evident that the maximum torque decreases with increased load and slip. This is in contrast with the polyphase motor, in which the field strength is controlled entirely by the stator and the maximum torque is not influenced by slip.

Capacity.—A polyphase induction motor, operated single phase, experiences a reduction in capacity mainly because, in the single-phase machine, there is but one working axis per pole pair. The torque is pulsating in character as contrasted with the sustained torque developed by a polyphase motor. The lower relative pull-out torque of the single-phase motor is also a factor. A three-phase motor, operated single phase

at the same voltage, will develop less than half its polyphase pull-out torque. The output must also be reduced to about 60 per cent of polyphase rating. If the single-phase voltage be made about 25 per cent higher than the polyphase voltage, the magnetization is increased and the pull-out torque improved. The distribution of losses is also better and the single-phase rating will then be about 70 per cent of the polyphase rating.

Rotor Resistance.—Rotor resistance affects the slip of a single-phase induction motor, increase in resistance requiring increased slip in order to afford increased slip voltage. Rotor

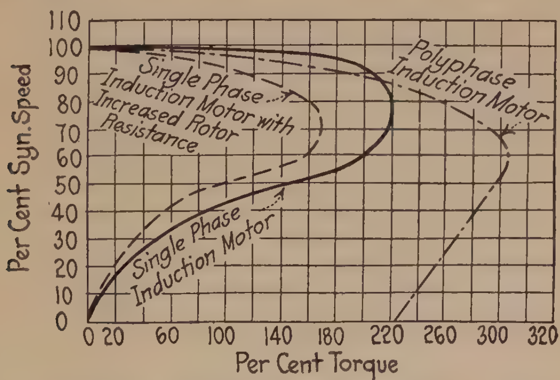

FIG. 85.—Comparative speed-torque characteristics of polyphase and single-phase induction motors.

resistance in a single-phase motor reduces the maximum torque also by its effect upon the speed field. The higher the resistance the more elliptical the resultant revolving field. The curves in Fig. 85 show how introduction of rotor resistance decreases the maximum capacity of a single-phase shunt induction motor. The use of rheostatic control for speed variation is thus hardly feasible for this type of machine.

Characteristics.—The torque of a single-phase induction motor varies as the square of the voltage applied to the stator windings. In this respect the single-phase motor is identical with the polyphase machine. The efficiency of the single-phase induction motor is lower than that of the polyphase motor. The magnetizing current is larger, increasing the primary cop-

per loss and decreasing the power factor. The presence of exciting current in the rotor conductors increases the secondary copper loss also.

Figure 86 shows the characteristics of a typical single-phase shunt induction motor. The speed characteristic of this motor is similar to that of the direct-current shunt motor and the polyphase induction motor. The regulation is exceptionally good under moderate loads but the speed drops off markedly upon overloads. The maximum torque of a motor equipped with a clutch is a little over 150 per cent full-load

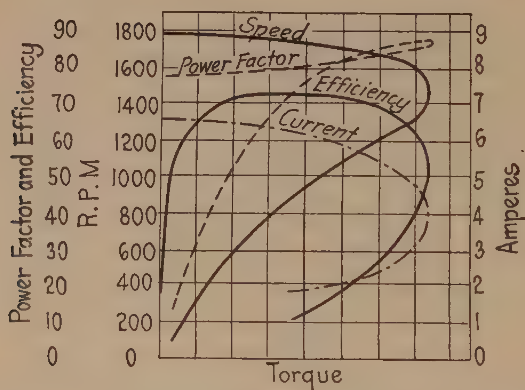

Fig. 86.—Operating characteristics of typical single-phase induction motor.

value inasmuch as at greater loads slippage occurs in the clutch. The power factor is low at all loads but increases rapidly and continuously with increase of load, being best at overloads. The efficiency is quite good for a motor of small size. Motors of this type are suitable for constant speed drives requiring light or moderate starting torque where starting is infrequent. They are often considered objectionable when connected to lighting mains inasmuch as the low power factor and heavy current at starting are detrimental to the voltage regulation. Their low power factor is objectionable in any case.

COMMERCIAL COMBINATION TYPES

Repulsion-starting Induction Motors.—Most applications demand a constant speed such as afforded by the shunt induction motor. The single-phase shunt induction motor has poor starting qualities, requires an auxiliary starting device and sometimes a clutch. Even with these features, little load can be accelerated and heavy current is taken. The series induction or repulsion motor, on the other hand, has very good starting characteristics. Motors have consequently been developed, popularly termed "repulsion-starting-induction" types, which start and run as series induction motors until a predetermined speed is attained. An automatic switch then short-circuits the rotor windings completely and the motor is transformed, in action, to the self-excited shunt induction type.

This motor is usually built with a single inducing winding distributed in the bore of the stator, this winding being connected across the line. The rotor is wound much like a direct-current armature. A commutator is provided, this usually being of the radial type to facilitate the design of the switching mechanism. This device is a centrifugal mechanism which short-circuits the commutator bars on their inner side. It also causes the brushes to be lifted from the commutator.

This double-acting motor, possessing high starting torque with moderate current input, is well adapted for driving pumps, air compressors or any drives where the full torque is required from standstill. The motor develops about full-load torque with full-load current at starting. It can develop more than three times full-load torque with about three times full-load starting current. The pull-out torque is about 175 per cent full-load value. Since the motor develops so good a torque with moderate current input, it is well suited to automatic starting and is frequently employed for this service. In operation the motor is essentially a constant-speed machine. It can therefore be employed for small line shaft drives or for almost any small constant speed machines. Century, Wagner and Westinghouse motors are among those of this general type.

Compensated Self-excited Shunt Induction Commutator Motor.—Another so-called "repulsion-induction" motor em-

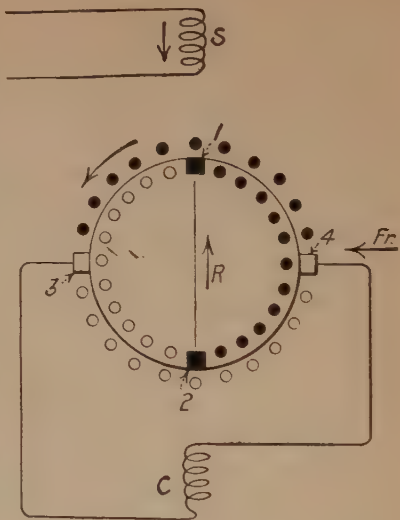

FIG. 87.

Compensated self-excited single-phase shunt induction commutator motor. (General Electric Type RI, with brushes on neutral).

At the instant shown and for an ideal motor:

1. Supply voltage is maximum.

2. Magnetizing current in *S* is zero.

3. Vertical inducing flux is zero.

4. Voltage induced in rotor appears at brushes 1 and 2. This voltage is maximum.

5. A voltage is generated due to cutting the inducing flux. This voltage is zero at instant shown. This exciting voltage appears at brushes 3 and 4.

6. A voltage is induced in *C* by vertical inducing flux. This voltage is maximum at instant shown. This compensating voltage is applied at brushes 3 and 4 and is in quadrature with the exciting voltage in that brush circuit.

7. A current flows through the rotor between brushes 3 and 4, due to items 5 and 6. The phase of this current depends upon the relative values of items 5 and 6. It is near maximum. (Outside dots and circles.)

8. The field *Fr* is set up by item 7. The phase of this field depends on the phase of item 7. It is near maximum.

9. A counter-voltage is generated due to cutting *Fr*. This voltage appears at brushes 1 and 2. Its phase depends on *Fr*. It is near maximum. It opposes, approximately the induced voltage, item 4.

10. Load current flows through brush short circuit 1 and 2, due to differences in magnitude and phase between the induced and generated voltages, items 4 and 9. This current is near maximum. (Shown by inside dots and circles.)

11. The above current sets up magnetizing force *R* which is reflected by a neutralizing force *S* caused by current taken from the supply. The phase of this current depends on the phase of item 10. It is near maximum.

12. Torque is produced through co-operation of items 8 and 10. It is near maximum.

13. The inducing flux and field *Fr* are in space quadrature and approximately in time quadrature. They set up the revolving field of the motor.

14. No torque at rest as *Fr* is primarily due to generated voltage (with brushes off neutral motor develops starting torque).

15. Motor has approximately constant speed characteristic as field *Fr* is largely independent of load.

ploying no centrifugal switch, is in use. This machine is similar in theory to the self-excited, single-phase shunt induction motor previously described. It comprises, in its simplest form, a stator with an inducing winding and a rotor provided with a commutator and two sets of brushes short-circuiting the winding along stationary axes at right angles to each other, with one brush axis coinciding with the axis of the inducing windings. The phase-compensated form of this motor is shown in Fig. 88.

In line with the inducing winding S are the short-circuited working brushes. The exciting brushes, located at right angles to the working brushes, are in circuit with the compensating winding C located in the stator coaxially with S. This machine, like the self-excited, single-phase shunt induction motor, has no starting torque but, if brought to a sufficient speed, it will reach and operate at a nearly synchronous speed with a shunt characteristic. Under these conditions, energy is conveyed to the rotor inductively along the axis of S and the rotor working circuit is that which is short-circuited coaxially with S. The exciting voltage is generated in the rotor by rotation in the inducing flux due to S and appears at the exciting brushes. This voltage is in quadrature with the line voltage because it is in phase with the inducing flux and produces the motor field Fr. Torque is produced by the energy current flowing through the working brushes reacting upon the speed or motor field Fr. This motor field is in time and space quadrature with the transformer field. Together they produce the resultant revolving field of the motor. The phase of the back voltage which opposes the working voltage induced by the transformer flux and appearing at the working brushes, depends on the phase of the motor field because it is generated by rotation of the rotor conductors in that field. The phase of the resultant difference between the working and back voltages determines the phase of the working current and therefore the power factor of the motor. Motors of this type are compensated for power factor by modifying the phase of the back voltage. This is accomplished in the motor shown in Fig. 87, by modifying the phase of the motor field which, in turn, modifies the phase of the back voltage generated by it. To modify the phase of this

motor field the phase of the exciting voltage is changed by introduction of a voltage of differing phase. The exciting speed voltage appearing at the horizontal brushes is normally in quadrature with the line voltage. A voltage in phase with the line voltage is injected into the exciting circuit by means of the stator winding C in which a voltage of the desired phase is induced by S. By changing the magnitude of this compensating voltage any desired degree of compensation can be obtained.

General Electric Type RI Motor.—The motor shown in Fig. 87 has little or no starting torque. To give this machine a decided starting torque the whole brush system is displaced in the General Electric type RI motor. Slightly displacing the brush system and, at the same time, opening the circuit of the brushes connected to the compensating winding would obviously bring about the very desirable series starting characteristics associated with the repulsion motor shown in Fig. 81. After such a machine has reached a sufficient speed, the compensating circuit can be closed. The displaced main brushes will tend to give the machine a series characteristic. The short-circuited exciting brushes will tend to give it a shunt characteristic. Such a machine actually shows the characteristics of a compound motor, its speed dropping more markedly with increasing load than is the case with a motor in which the brush system is located as shown in Fig. 87. It is possible to secure satisfactory starting performance by displacing the brush system, as previously explained, without opening the circuit of the exciting brushes and compensating winding. Under these conditions the closed compensating circuit will reduce the starting torque and increase the starting current but will deprive the machine of its series characteristic in normal operation and will also improve its power factor.

The compensating voltage injected into the exciting circuit can be obtained from an outside transformer connected in parallel with S or, as indicated in Fig. 87, by a winding coaxial with S. The direction of rotation can be reversed by moving the brush system to the other side of the S axis or by shifting the axis of S. The latter means is adopted in the larger motors of this type and is achieved by dividing S into two

suitably proportioned and displaced groups of windings and reversing the current through one of the groups.

Characteristics.—The discussion of the action of this type of motor has brought out the fact that it is a machine with an approximately constant speed characteristic and that the power factor is near unity. In addition, it has good starting torque, developing full-load torque with about 200 per cent current input and starting three and one-half times full-load torque if thrown directly upon the line. Motors above 5 hp. are

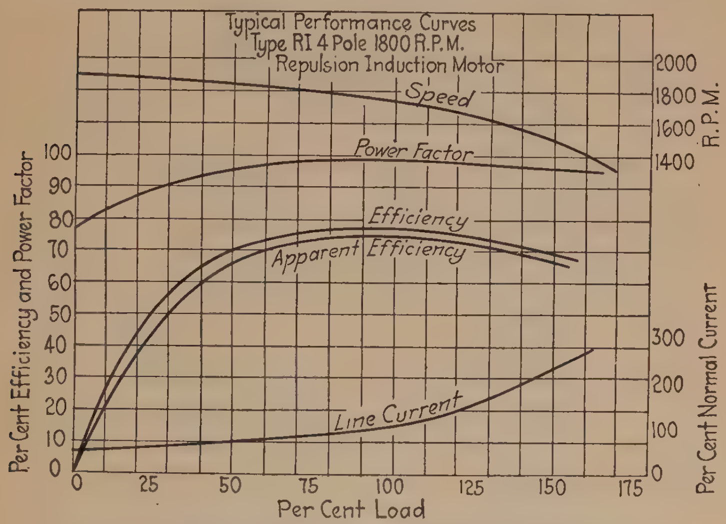

FIG. 88.—Operating characteristics of a single-phase RI motor.

usually provided with a starting rheostat to limit the starting current. The power factor at starting is high because of considerable losses and acceleration is quiet. The pull-out torque is very high, the machine slowing down with overloads and acting much like a compound motor. The characteristics of a typical motor of this design are shown in Fig. 88. The connections for a reversible motor of this type are shown in Fig. 89.

Variable Speed Duty.—Motors as above described can be used for variable speed service where but a moderate speed range is demanded. If resistance be inserted in the circuit of the energy brushes the effect is similar to increasing the rotor

resistance of a polyphase induction motor or to the insertion of resistance in series with the armature of a direct-current motor, the speed being decreased in proportion to the resistance inserted and in proportion to the load carried. Insertion

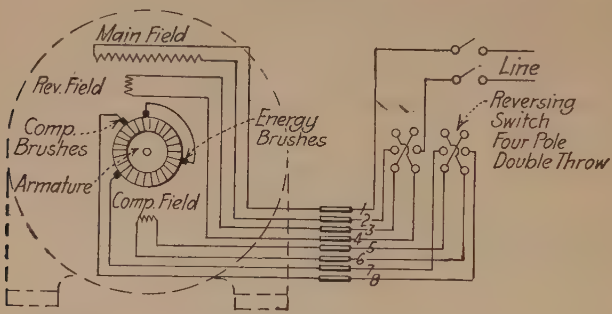

FIG. 89.—Connection diagram of a reversible RI motor.

of resistance in the exciting circuit is like weakening the field of a direct-current shunt motor, increase in speed resulting. The connections of an adjustable speed RI motor are shown in

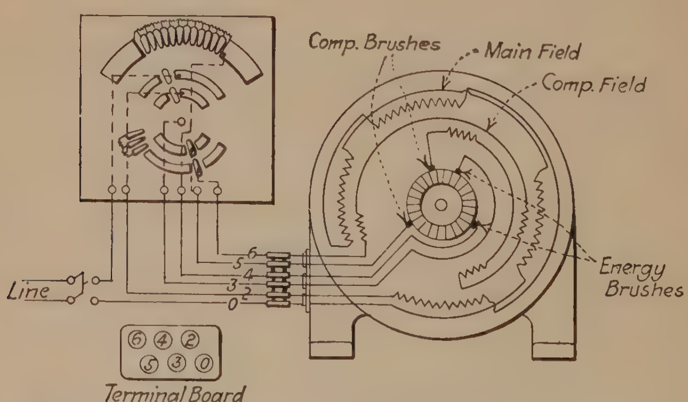

FIG. 90.—Connection diagram of an adjustable speed RI motor.

Fig. 90. The range of control runs from 40 per cent reduction below normal speed at full load with resistance in the energy circuit, to 10 per cent above normal speed with resistance in the exciting circuit.

The Wagner BK Motor.—The so-called BK or "unity power factor" motor is a commercial type having interesting features. It combines the starting characteristics of the series induction motor, the constant speed qualities of the squirrel-cage machines and the high power factor of the compensated self-excited shunt induction motor. The scheme of connection is shown in Fig. 91. The motor has a distributed primary inducing winding S and a compensating winding C

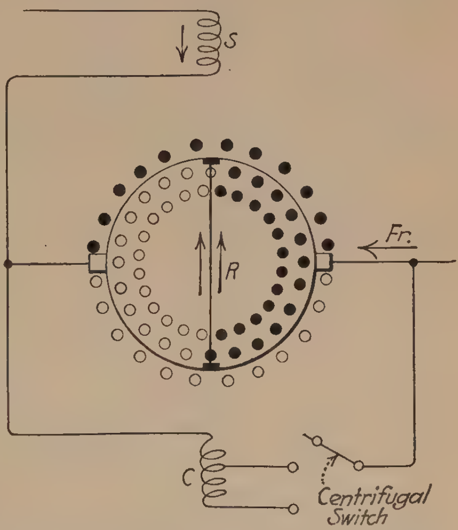

FIG. 91.

Connection diagram of the single phase Wagner BK motor.

Starting:
Centrifugal switch is open — motor operates similar to the single-phase series induction motor with rotor excitation, shown in Fig. 82. Squirrel-cage winding does not produce torque until motor attains speed. It tends to reduce the magnitude of *Fr.*

Running:
Centrifugal switch is closed. Motor acts as a combination of the compensated self-excited shunt induction commutator motor shown in Fig. 87, and the self-excited shunt induction motor shown in Fig. 83.

on the stator. The rotor carries an inner squirrel-cage winding and an outer winding connected to a commutator. The two windings are separated by a "magnetic bridge" of iron intervening between them. There are two sets of brushes on the commutator, the short-circuited working brushes in the axis of the inducing winding and the exciting brushes at right angles to the former.

At starting the inducing winding S is in series with the commuted winding on the rotor through the exciting brushes. After a certain speed has been reached the exciting brushes

are also connected to the compensating winding either automatically or by hand.

At starting the arrangement is exactly like that of Fig. 82, plus a squirrel cage on the rotor. Without a squirrel cage the machine would have all the excellent and more than sufficient starting qualities set forth in connection with Fig. 82, but it could only be used where a series characteristic is not objectionable. This machine depends for its torque on the rotor ampere-turns in the axis of S and on the motor flux perpendicular to this axis. The addition of an ordinary squirrel cage would increase the rotor ampere-turns in the axis of S but would neutralize and reduce the flux Fr, at right angles to S, to a negligible value and also adversely affect its phase. Yet if such a motor did attain a nearly synchronous speed it would hold it as closely as all squirrel-cage motors do and it would have a shunt operating characteristic. The desired result is secured by a compromise. The squirrel cage is entirely embedded in the rotor iron while the commuted winding is placed close to the periphery leaving a certain amount of iron between the two windings. This arrangement not only makes the squirrel cage less effective at starting but actually provides an iron path which can be followed by any flux set up by the commuted winding without linking with the squirrel cage. In other words the mutual inductance between the squirrel-cage and the rest of the windings is considerably reduced. As a result, the current passing the exciting brushes is able to force enough flux of the correct phase through the magnetic bridge of the rotor to produce a sufficient starting torque in conjunction with the vertical ampere-turns in the commuted winding. The squirrel-cage motor of the combination shown in Fig. 91, comprising the squirrel cage on the rotor and the inducing stator winding S, is ineffective at rest and at low speeds, but as the speed increases it develops the usual operating characteristics of its kind. Near synchronism it tends to give the combination a shunt characteristic and thus limits its speed. The magnetic bridge is so dimensioned that the squirrel-cage feature allows of about twice the full-load torque at starting and yet holds the motor speed at no-load to a few per cent in excess of the synchronous. The speed is slightly supersyn-

chronous because the commuted winding tries to give the machine a series characteristic, producing an always positive torque. The positive squirrel-cage torque decreases with rising speed until synchronism is reached, when said torque is zero. Above synchronism the squirrel-cage torque is negative and increases rapidly with increasing speed. The balance between the series and shunt torques is therefore reached above synchronism. The machine can be operated with this starting connection. Under load the speed very rapidly drops to just below synchronism and then remains nearly constant up to full-load.

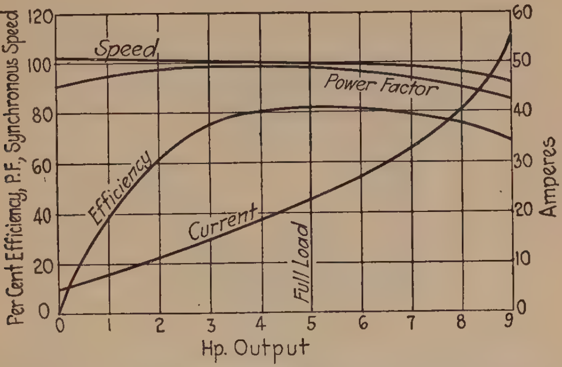

FIG. 92.—Operating characteristics of the BK motor.

The efficiency of the combination is, however, considerably improved if the antagonistic series feature is now eliminated. This is readily achieved by short-circuiting the exciting brushes after the motor has reached its operating speed. With the exciting brushes short-circuited the motor is a combination of a squirrel-cage shunt induction motor with the corresponding commutator type machine, *i.e.*, that shown in Fig. 87 with winding *C* eliminated. Both elements of the combination have a shunt characteristic at nearly synchronous speed and there is no internal conflict. To make the best use of the available material the machine shown in Fig. 91 is always compensated when up to speed. This is very simply achieved by closing the exciting brushes over the compensating winding *C*, instead of short-circuiting them. The degree of compensa-

tion can be varied by including more or less of C in the exciting circuit. With C in circuit the machine is a combination of a squirrel-cage shunt induction motor with a compensated self-excited shunt induction commutator motor. The operating characteristics of one such motor with moderate phase compensation are illustrated in Fig. 92.

General Electric Type BSS Motor.—Nothing is changed as to the operating characteristics of the motor shown in Fig. 82, if a series transformer of single or double-winding type is

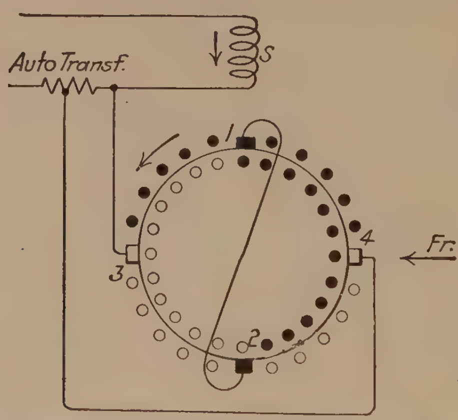

FIG. 93a.—Single-phase series induction motor with rotor excitation and movable brushes—brushes in normal position. (Same as shown in Fig. 82, except current for exciting circuit is taken from series transformer.)

inserted between the inducing winding S and the horizontal exciting brushes as indicated in Fig. 93. This type of motor, with the addition of a brush-shifting device, is in use for variable speed work. Figs. 93a, b, and c show the brushes in three positions. The effects of shifting the brushes differ according to the direction in which the brush system is displaced and according to the transformation ratio of the auxiliary transformer. In Fig. 93a all of the turns carrying the short-circuit current passing brushes 1–2 do duty as armature or energy turns whereas all the rotor turns carrying the current conducted through the brushes 3–4, do duty as field or exciting turns. Any displacement of the brush system causes each

set of turns to do dual duty, partly as armature and partly as field turns. The armature turns of one set may help or oppose the armature turns of the other and the same is true of the field turns. The result is that the effective armature and field turns vary with varying brush position. The effective ampere-turns depend on the turns and current in each circuit.

Suppose the transformation ratio of the auxiliary transformer is such that the ampere-turns in the axis of the brushes 1–2

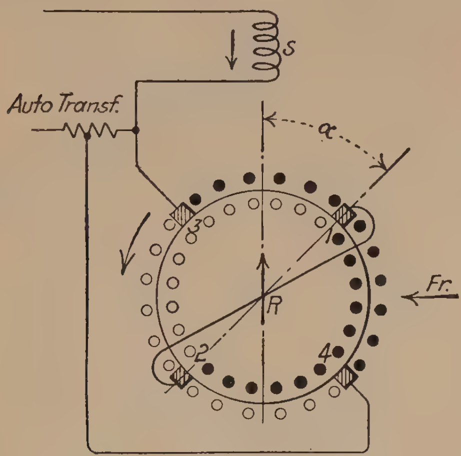

FIG. 93*b*.—Brushes shifted against the direction of rotation. Energy current flowing through brushes 1 and 2 and exciting current flowing through brushes 3 and 4 are cumulative as to vertical axis and opposed as to horizontal axis. Value of field *Fr* depends on relative values of energy and exciting currents and on amount of brush shift. Field *Fr* is weak and speed is high.

are equal to those in the axis of the brushes 3–4. If the brush system is now displaced against the direction of rotation, as in Fig. 93*b*, the ratio of effective armature to effective field ampere-turns will increase until the effective field ampere-turns become zero for a displacement of 45 deg. If the brush system is displaced in the direction of rotation as shown in Fig. 93*c*, then this ratio will decrease until the effective armature ampere-turns become zero for a displacement of 45 deg. The actual results will not be as stated because the ever-varying

magnetizing current of the system makes it impossible to keep the transformation ratio constant without adjustment. Speed variation can be had by moving the brush system in the one or the other direction, by changing the transformation ratio of the auxiliary transformer or by a combination of these methods.

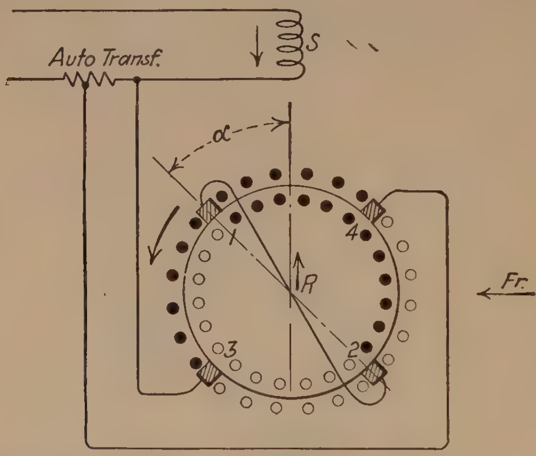

FIG. 93c.—Brushes shifted with the rotation. Energy current through brushes 1 and 2 and exciting current through brushes 3 and 4 are cumulative as to horizontal axis and opposed as to vertical axis. Field *Fr* is strong and speed is low.

This type of motor has a series characteristic as shown in Fig. 94, where curves for several brush positions are plotted. At light load, little speed change is effected by shifting the brushes. The load speeds, for a given transformation ratio, depend upon the brush position and also upon the load. Hence the character and amount of load must be carefully considered in selecting the motor to insure that the desired speed range may be obtained.

Motors of this type afford a 2 to 1 speed range against full-load torque. Greater speed ranges may be obtained with special windings and perhaps a larger frame as heating and commutation at low speed are limiting factors. Where the torque falls rapidly with reduced speed a wider speed range by brush-shifting may be permitted.

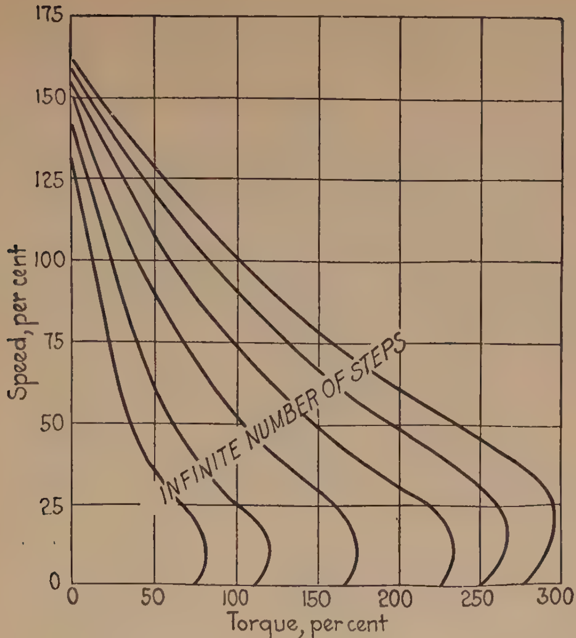

FIG. 94.—Speed-torque curves of a series induction motor with movable brushes, type BSS.

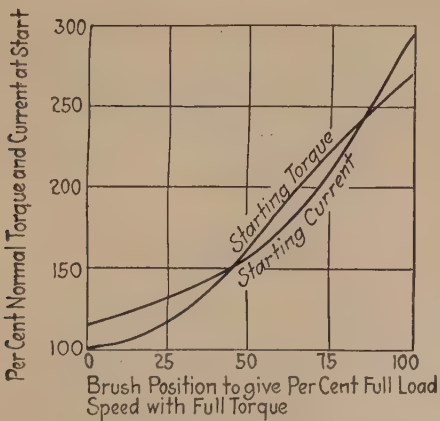

FIG. 95.—Starting performance of a series induction motor with movable brushes, type BSS.

The speed and torque of motors of this type may be regulated, not only by brush-shifting, but also by adjustment of taps in the series transformer. In this way the ratio of exciting current to main current may be changed and the speed and the torque modified.

Figure 95 shows the starting performance of a motor of this type. The motor may be started with the brushes in any position but a low-speed position is preferable, minimizing the starting current inrush. Efficiency and power factor curves for a motor of this type showing full-load torque and half-load torque values, are given in Fig. 96.

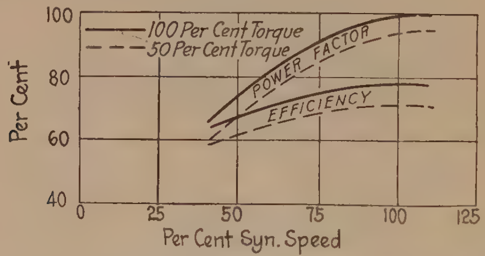

FIG. 96.—Efficiency and power-factor curves of a series induction motor with movable brushes, type BSS.

Brush-shifting motors are built in sizes from $\frac{1}{4}$ hp. to $7\frac{1}{2}$ hp., at 1,200 and 1,800 r.p.m. rated speeds. The larger motors may be reversed by shifting the brushes sufficiently far across the live neutral position, but the better way is to reverse the current through the circuit comprising the brushes 1 and 2. The control for motors of this type includes a line switch and some form of brush-shifting mechanism.

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CHAPTER IX

THE BRUSH-SHIFTING POLYPHASE COMMUTATOR MOTOR

The polyphase induction motor is not well adapted for adjustable speed service except for large units where the use of auxiliary apparatus in the secondary circuit is feasible. The demand for an efficient alternating-current motor affording speed control in small increments over a considerable range has led to the development, by the General Electric Co., of a brush-shifting type of adjustable varying-speed polyphase commutator motor.

Theory of Action.—The action of this motor may be best understood if its single-phase prototype is first considered. This is essentially a neutralized single-phase series motor with adjustable brush position. It is briefly described in Chap. VIII, and shown in Fig. 80, which is reproduced in Figs. 97*a*, *b*, *c*, in which different brush positions are shown. We will consider the relations existing as the angle α, denoting the displacement from the live neutral position, is modified. There are three magnetizing influences in this machine. The stator ampere-turns create a magnetizing force N along a vertical axis. The rotor ampere-turns in the two arcs $(180–2\alpha)$ set up an opposing magnetizing force R. The rotor ampere-turns in the two arcs 2α set up the field Fr. The fluxes resulting from the forces N, R, and Fr are in time phase as they are set up by the same current. The flux Fr reacts with the current in rotor conductors $2(180–2\alpha)$ to produce a counter-clockwise torque. The direction of the torque resulting from reaction of the vertical flux on rotor conductors $2(2\alpha)$ depends upon the direction of that flux. This, in turn, depends upon the relative values of N and R. If N predominates, this torque will be counter-clockwise. If R predominates, this torque will be clockwise (with the brushes in the position

shown in Fig. 97*a*). The net torque of the motor depends upon the relative values of the individual torques.

When α is small, *Fr* is small but the rotor turns $2(180-2\alpha)$ constitute a relatively large portion of the total rotor turns which are effective in reacting upon *Fr* to produce counter-clockwise torque. As α increases, *Fr* increases but the turns reacting with *Fr* decrease. When α is 90 deg. there is no torque due to *Fr* as the term $2(180-2\alpha)$ is zero and the torque-producing influence of half the rotor conductors is opposed by that of the other half. When α is either 0 or 90 deg. the torque due to *Fr* is zero. For intermediate values of α, the torque

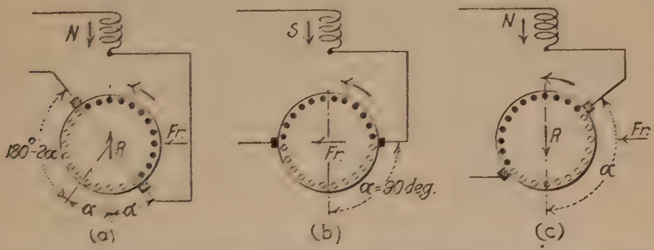


FIG. 97*a*, *b*, *c*.—Single-phase prototype of the polyphase series motor with movable brushes.

due to *Fr* is in a counter-clockwise direction. When α exceeds 90 deg., the torque due to *Fr* is in a clockwise direction.

As previously stated, the torque due to reaction of the rotor current with the vertical flux depends upon the relative values of N and R. If $R = N$, the net torque due to vertical flux is zero. If N is greater than R, the influence of N predominates and vice versa. With a given load current N is constant, regardless of the brush position, while R varies as α is modified. When α is small R is large, since most of the rotor conductors then have a vertical magnetizing influence. As α increases, R decreases. Thus, with α small, R may predominate over N, to produce clockwise torque. This torque will be small since the conductors reacted upon, $2(2\alpha)$, are few in number. When α increases, N may predominate to produce counter-clockwise torque, aiding the torque due to *Fr*. When α is 90 deg. all the torque is due to N, which now becomes S, as in a simple series motor. When α is greater than 90 deg., the torque due to *Fr*

is in a clockwise direction, rising as α increases past 90 deg. and falling as α approaches 180 deg. The direction of R is reversed so that both R and N cooperate to produce counter-clockwise torque. This torque decreases as α approaches 180 deg., since the rotor conductors reacted upon decrease in number. It should thus be evident that the net torque of this motor depends upon the brush position. The exact relations depend upon design factors. At any brush position the motor has a series characteristic, the field strength and speed varying with the load. With a given load, a change of brush position, involving a change in motor torque, causes a change in speed. This motor has at each brush position a series characteristic with the speed adjustment achieved by shifting the brushes.

When the angle α is zero, the rotor magnetizing influence R is all in a vertical direction and is directly opposed to the stator magnetizing force N. The impedance of the motor is therefore low and, if full voltage be applied, a heavy current will flow. If the angle α be 180 deg., the magnetizing influences R and N are cumulative. This gives the motor high impedance and greatly restricts the current flow and consequently the torque developed. The torque capacity of the motor varies with the brush position, due in part to the varying impedance.

If the angle α be zero, a shift of the brushes in either direction causes torque and rotation in that direction. This position is called the live neutral. If the angle α be 180 deg. a shift of the brushes in either direction causes torque and rotation in the reverse direction to the shift. This position is called the dead neutral.

Similarity to Direct-current Motor.—The principle upon which the brush-shifting motor is based, is evidenced in any direct-current non-interpole motor when its brushes are shifted from the neutral position. As was explained in Chapter IV, when the brushes of a direct-current motor are in the neutral position, the armature magnetization or cross field is displaced 90 magnetic degrees from the main field and thus has no influence on the speed of the motor other than indirectly through saturation due to distortion of the main pole flux. When the brushes are shifted in a direction against the rotation,

the armature cross field has a component which opposes and thus weakens the main field and thus increases the motor speed. When the brushes are shifted in a direction with the rotation, the armature cross field has a component which assists and thus strengthens the main field and thus decreases the motor speed. If the brushes were shifted a full 90 magnetic degrees in either direction from the neutral, points of no torque would be found. The alternating-current brush-shifting series motor functions along entirely similar lines. If the brushes of a direct-current motor be displaced far from the neutral position, severe sparking occurs. In the polyphase alternating-current brush-shifting motor this difficulty is minimized by winding the armature for a low voltage which is supplied from the secondary of a series transformer. Inter-relations between phases, later explained, also improve commutating conditions.

Polyphase Motor.—The polyphase motor is simply the superposition of two or three single-phase motors. The schematic arrangement for a two-phase motor is shown in Fig. 98. Each phase acts independently of the other along the same lines as indicated for the single-phase motor, the speed-torque and brush-shift-torque characteristics remaining the same. The polyphase motor commutates better, however, and has a better power factor. It should be noted that the two coils N_1 and N_2, located 90 deg. apart and carrying currents in time quadrature, will cause a rotating field, just as in an induction motor. The direction of the rotation of the rotor depends entirely upon the brush position and is independent of the direction of rotation of the revolving field. The direction of rotation of the field depends upon the relative phase connections of the stator phases. The stator field should be made to revolve in the same direction as the rotor since the commutation and the power factor are both more satisfactory with this mode of operation.

The effect of superimposed phases upon commutation may be seen if we first return to the neutralized single-phase self-excited series motor shown in Fig. 97. We find there two currents in the short-circuited coils, one generated by rotation in the flux N or R, this current being in phase with N, R, and Fr.

The other short-circuit current is induced by Fr and lags 90 deg. behind Fr. The induced current is independent of the speed, the generated current varies directly with the speed. Considering the polyphase motor of Fig. 98, we find that the short-circuit current generated in brushes b_1 and b_2 by Fr_2 opposes that induced by Fr_1. Likewise the short-circuit current induced in the same brushes by N_2 is in opposition to that generated by N_1 or R_1. Like conditions occur at the other brushes. The interphase influence is thus beneficial to commutation. It should be noted, however, that these relations hold true only when the stator field revolves in the same direction as the rotor. With stator field reversed, the induced and generated short-circuit currents combine instead of opposing each other and thus render commutation very poor. It should also be noted that induced short-circuit currents, whose values are independent of speed, are opposed by generated short circuit currents having values dependent upon the speed. At synchronous speed the opposition is complete and commutating conditions are excellent. At lower speeds conditions are less favorable. Near standstill, sparking may be severe.

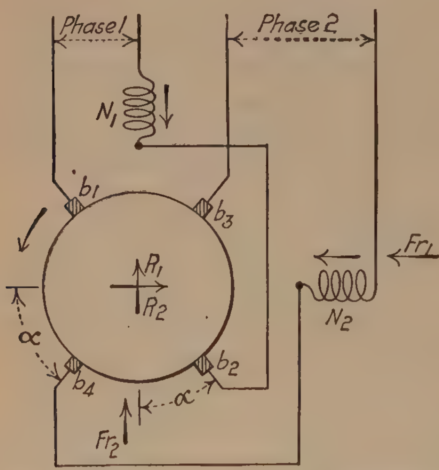


FIG. 98.—Connections of a two-phase neutralized, self-excited series motor with movable brushes.

Commutating conditions may be viewed in another manner. At standstill it is evident that the rotating field will generate considerable current in the commuted coils under the brushes. At synchronous speed, no such currents would be generated and commutation should be good. If the field is rotating in the reversed direction, the short-circuit currents are greater

because of the increased rate of cutting flux. The commutating conditions are then unfavorable.

When the motor is installed a check should be made to insure that the direction of rotation of the armature and that of the revolving field are the same. This may be done by observing an ammeter as the motor is started and accelerated with a fixed brush position. If the line current decreases as the speed increases, the motor is correctly connected. If the line current remains constant or increases as the speed increases, it indicates that the motor is running against its field rotation. The direction of rotation of the revolving field can then be

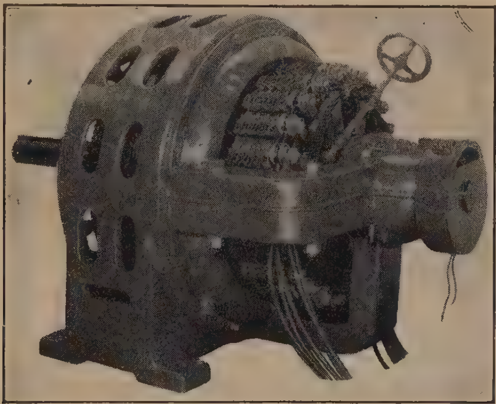


FIG. 99.—Polyphase brush-shifting series motor.

reversed by interchanging two line leads, just as with a polyphase induction motor. Care should be taken not to disturb the relative field and armature connections of any phase. This motor constitutes a number of superimposed single-phase motors, all of which must have their armatures connected to their fields in like manner. When the motor is connected so that the stator and rotor windings of each phase are properly related, the motor will develop the same torque and take the same current from the line when operating on any one of the phases. A check should be made to insure this condition.

Description.—A commercial polyphase brush-shifting motor is shown in Fig. 99. The stator of this motor is similar to

that of an induction motor of the same rating, being of about the same size and weight. In some cases identical stators are used. The armature resembles that of a direct-current motor. The commutator is rather large inasmuch as a low armature voltage is used to avoid excessive sparking. The brush yoke has a stud for each pair of poles in each armature phase. As later explained, there may be more armature phases than field

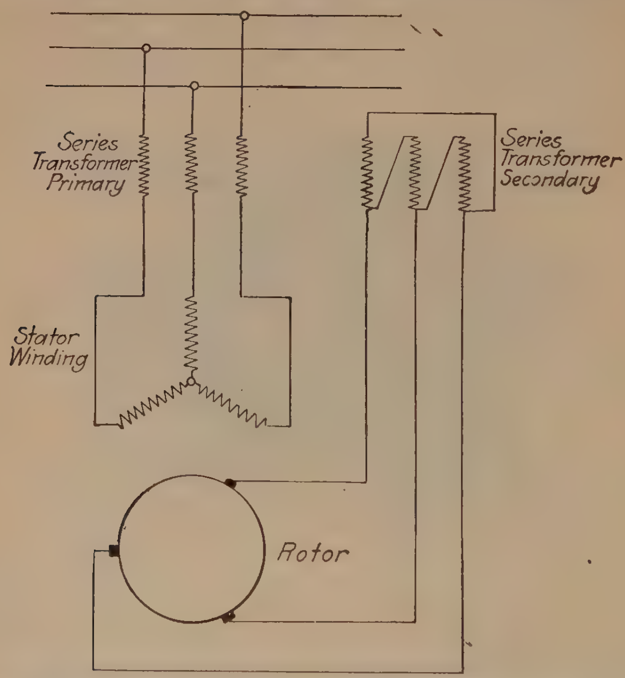


FIG. 100.—Connections of a three-phase brush-shifting series motor.

phases. Series-wound armatures or multiple armatures with equalizing connections require but one brush stud per phase.

Connections.—Figure 100 shows the scheme of connections for a three-phase motor of this type. A series transformer is generally used to step down the voltage for the armature as low voltage is necessary to good commutation. The secondary of this transformer is connected for three phases and the armature has three sets of brushes per pole-pair. The transformer, by

its ability to become saturated, limits the no-load speed of the motor to a safe value, which is usually about 150 per cent normal.

The characteristics of the brush-shifting polyphase motor depend to a considerable degree upon design factors, such as ratio of armature to stator ampere-turns. In order to gain flexibility in performance these factors may be arranged for adjustment in the field. The armature relations are modified by means of taps in the step-down transformer. Light load operation is more stable if the primary turns in this transformer are reduced below the most effective full-load ratio. The tap to be selected depends upon the relation of motor rating to load handled.

The use of a six-phase armature connection improves the commutation. In a direct-current motor the current in the commuted coil is reversed and an inductive kick occurs, this being an influence detrimental to commutation. In a motor such as shown in Fig. 98, the current is not reversed but is advanced 90 deg. as the coil passes under a brush. In a six-phase armature the current is advanced but 60 deg. under each brush and the inductive kick is thus minimized. The armature may have any number of phases, independent of the stator, just as in an induction motor, as the revolving fields set up by the stator might be considered as composed of any number of phases. It is usual to provide a six-, nine-, or twelve-phase armature, since these relations may be most readily obtained by transformation from two- or three-phase primaries.

Effect of Frequency.—The brush-shifting polyphase motor is better suited for use on 25-cycle circuits than on 60-cycle circuits. The commutation is better at the lower frequency and the possible output from a given commutator and frame is greater with low than with high frequency. This is primarily due to the fact that higher voltage per phase and more rotor phases may be used with a given number of brush studs due to the lesser number of poles for a given speed. This results in less current per rotor phase and increases the capacity of the commutator.

Characteristics.—The speed-torque characteristics of a polyphase brush-shifting motor are shown in Fig. 101. A number of curves are given, each representing the action with a given

brush position. The motor has a series characteristic, the speed varying materially with small load changes, particularly with the brushes in the low-torque position. This feature renders this type of motor ill suited for any variable load drives in which approximately constant speed is desired. The motor is not strictly an adjustable speed machine. It may be best described as an adjustable varying-speed machine. It is similar in action to the induction motor with rheostatic control. In the matter of efficiency, however, the brush-shifting type is superior.

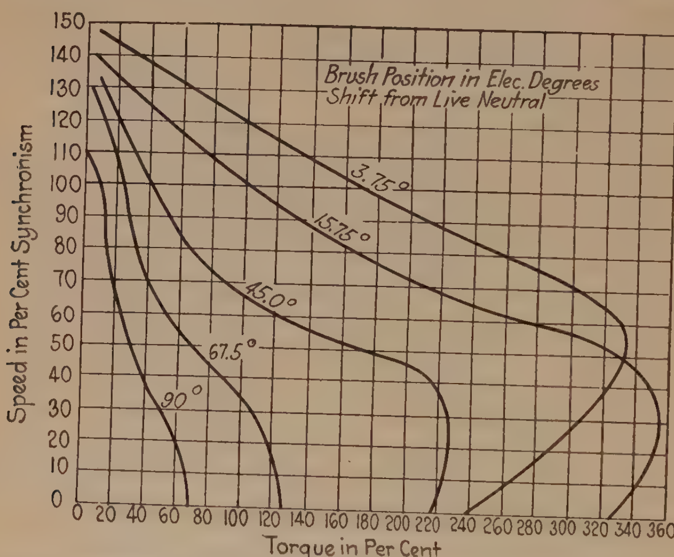


FIG. 101.—Speed-torque characteristics of a polyphase brush-shifting motor with different brush positions.

The rated maximum full-load speed is usually about $12\frac{1}{2}$ per cent above synchronous speed. At light loads somewhat higher speeds may be reached.

Speed Range.—The speed range obtainable with the brush-shifting motor depends in part on the service. If the load is very light it is impossible to vary the speed widely without rather unstable characteristics. If the load at all speeds is heavy the allowable degree of brush shift is restricted by the limited torque capacity of the motor when α nears 90 deg.

Under ordinary conditions a reduction to about 40 per cent of maximum speed is permissible. Where the torque decreases rapidly with speed, as in a fan, a greater brush shift may be allowed and a reduction to 25 per cent maximum speed obtained. Torque, rather than commutation, is generally the limiting factor. Where a wide speed range is required with approximately constant torque, a larger frame is generally necessary. The specification of an unnecessarily wide speed range is therefore to be avoided.

It is evident that too great a brush shift may reduce the

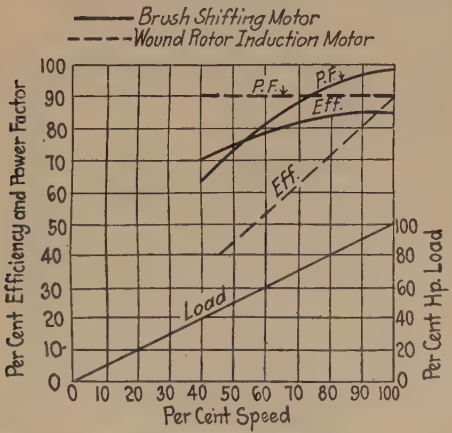


FIG. 102.—Curves showing comparative efficiency and power factor of a brush-shifting motor and a wound-rotor induction motor with varied speed on a constant torque load.

torque to a point where it does not exceed the load torque. The motor then stalls. To avoid damage in this situation, a centrifugal disconnecting switch is provided for some applications which automatically disconnects the motor from the line when the speed drops to a point of possible injury. The tripping point of this device may be adjusted to suit the load conditions existing.

Efficiency and Power Factor.—The efficiency and power factor of the brush-shifting motor may be seen from the characteristic curves, Fig. 102, which show these features in a typical motor. It will be seen that the efficiency at reduced

speeds is considerably better than that of the induction motor with rheostatic control, whereas the power factor at reduced speeds is somewhat lower.

Part of the excitation of the brush-shifting motor is supplied to the rotor through the series transformer. This tends to give the motor a better power factor than that of a corresponding induction motor in which all the excitation must be supplied through the stator. The inter-phase effect in the armature is also beneficial to power factor.

It is possible to materially improve the power factor at reduced speed by decreasing the stator voltage. If this is done,

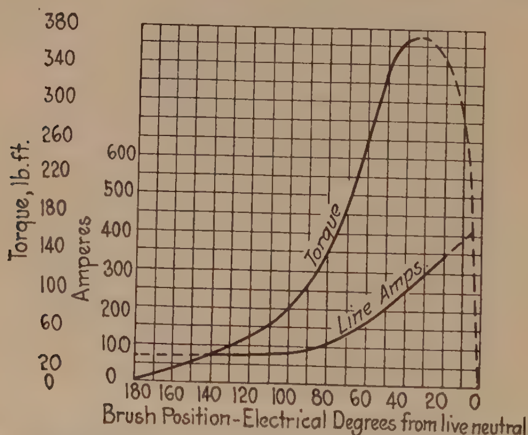
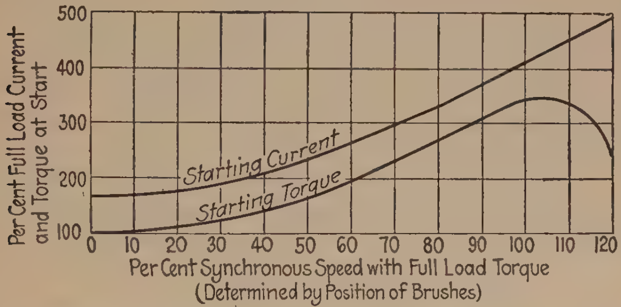


FIG. 103.—Starting torque and line current of a polyphase series motor with different brush positions.

the speed for a given brush position is lowered. The improvement in power factor results from a decrease in magnetizing current at the lower voltage. This voltage reduction may be accomplished by bringing out six stator leads and connecting in delta for speeds down to about 33 per cent maximum, the Y connection being used for speeds below this. As the torque is also affected, this procedure is only utilized for drives where the torque decreases rapidly with the speed.

Starting Performance.—Previous mention was made of the fact that, when α approaches 180 deg., the impedance is high and the torque developed is relatively low. The brush-shifting

motor may be started by connecting directly to the line with the brushes near the dead neutral position. Due to the high impedance the current inrush is low and the small torque developed insures a smooth start. The motor is then accelerated to the desired speed by shifting the brushes to decrease α, the torque capacity increasing likewise. These conditions are evident in Fig. 103, which shows torque capacity and corresponding line current for various brush positions. The maximum starting torque is developed in this instance when α is 35 deg. This torque is often 300 to 400 per cent rating but the current demand is also high. Figure 104 shows similarly



104.—Starting torque and current of a brush-shifting polyphase series motor with different brush positions.

the starting torques and currents for various brush positions such as to give a range of speeds with full-load torque.

Controller.—The only control required for this motor is a line switch panel arranged to give overload and under-voltage protection. If the Y-delta scheme is used, switching equipment to change connections is necessary. The brush shifting may be done manually by turning a hand-wheel which moves the brush yoke through a worm and wheel mechanism, or a pilot motor may be employed, affording remote control.

Application.—Standard motors of this type are built in capacities of 5 hp. to 40 hp. Larger motors can be built, the maximum capacity being limited by commutation considerations. The limiting sizes are about 175 hp. at 1,200 r.p.m. and 350 hp. at 600 r.p.m. If a narrow speed range only is desired,

the motor may be rated on a constant horsepower basis. For a wide speed range the motor is rated on a constant torque basis, or very often, in the larger sizes, on the basis of torque decreasing with the speed.

The cost of the brush-shifting motor is relatively high, being on the order of 175 to 300 per cent of the cost of an equivalent wound-rotor induction motor and control.

The brush-shifting motor parallels the wound-rotor induction motor so closely in general characteristics that it is adapted for use only where that type of motor would also serve. The principal advantage of the brush-shifting motor is its relatively high efficiency. Its good starting performance is also a consideration. It affords an infinite number of increments of speed adjustment within its range. The simplicity of the control equipment is also a factor. The principal disadvantages are high cost, greater complexity and the presence of a commutator and brushes. This type of motor, because of its higher efficiency, is particularly well suited for driving constant duty fans or pumps, drives having suitable torque requirements and whose constant operation emphasizes the importance of efficiency. Since the brush-shifting motor is more costly than the induction motor, its use is warranted only where continuous service renders the power saving sufficient to warrant the extra investment.

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CHAPTER X

ELECTRIC MOTOR CONSTRUCTION FEATURES

Electric motors are called upon to drive a wide variety of machines and to fulfill a diversity of demands. It is impossible to build a single line of motors which will meet the needs of the many different fields of application. The service demands are classified, however, and a few lines of motors built, one of which will be suitable for any ordinary application. In addition to the general lines, machines are available for special cases. There is also a pronounced tendency toward the adaptation of standard motors, or at least standard working parts, for individual application to driven machines through the use of special frames, mountings or mechanical features.

DIRECT-CURRENT MOTORS

Standard direct-current motors are available in several general types of construction. The most prominent types are: general purpose motors, enclosed box frame motors or crane and hoist motors, railway and mine traction motors and mill type motors.

General Purpose Motor.—The commercial general purpose motor is the prevailing type. It is standard with shunt or compound windings, 20 to 40 per cent compounding being afforded. Constant speed motors of this class are normally rated on a continuous duty basis. Adjustable speed motors are rated both for continuous and for intermittent duty. Motors of this construction having special features and ratings are adapted specifically for elevator service. General purpose motors are of open construction, although semi-enclosing and totally enclosing covers may be added, the latter reducing the heat-dissipating ability and lowering the horsepower rating of the machine. Being widely used, motors of this class are sold

under keen competition and their design and construction represents a compromise between sturdiness and cost. Figure 105 shows a typical motor of this familiar type.

The frame of the open type motor comprises essentially the magnetic yoke, the bearing brackets and the supporting feet. The yoke is of ring form, because this design has been found most economical in material, and may be of cast iron, cast steel, rolled steel or laminated steel. Cast iron has comparatively low magnetic permeability so that a large cross-section is required. Cast steel is commonly used. One prominent

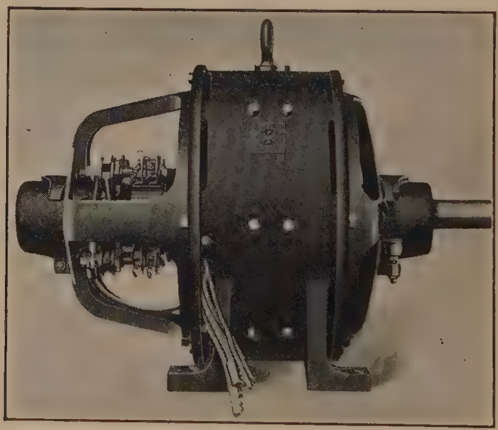

Fig. 105.—General purpose direct-current motor.

commercial design makes use of a rolled-steel ring arc-welded at the joint. The stated advantage of a rolled over a cast yoke lies in the certainty of a uniform magnetic circuit. Castings may sometimes have blow-holes which lead to uneven flux distribution, affecting performance. In the larger motors it is desirable to have the frame split horizontally so as to afford access to the armature.

Crane and Hoist Motors.—Box frame or crane and hoist motors are designed for service quite different from that of the general purpose type. This motor is not ordinarily a continuous duty machine. It is used extensively for crane and hoist service and for the many applications requiring great turning

effort for short periods, the motor being commonly under the control of an operator while running. Motors of this type are commonly series-wound to afford maximum starting power and to require the minimum number of collector bars when used on moving parts such as cranes. Motors with about 10 per cent compounding are furnished, however, to restrict the light-load speed when this is desirable. These motors reach excessive speeds when operated without load and must always be geared, coupled or chain-connected so that the load cannot be entirely removed. The service being irregular, these motors are rated on an intermittent duty basis.

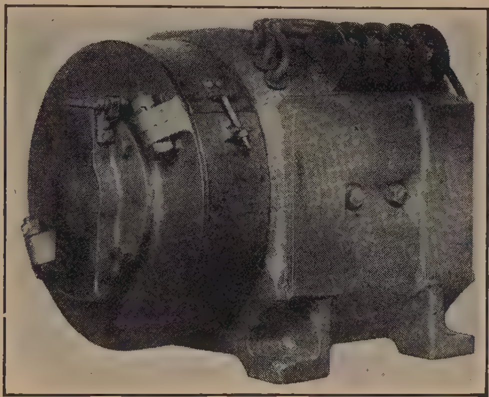

Fig. 106.—Crane and hoist motor.

Crane type motors are completely or largely enclosed because they are commonly located in dirty or damp places or exposed to the weather. They are somewhat more rugged than general purpose motors because the high torque duty and irregular service impose greater stresses upon them. The frame is usually of cast steel, of box or barrel shape, with four supporting feet. The frame should be split horizontally to permit access to and removal of the armature in places of difficult access such as cranes. Back-axle or countershaft brackets are often supplied, being commonly bolted to planed pads on the side of the frame. Pads are also provided on the ends of the frame for mounting a brake and the shafts are made with double

extensions for this purpose. Like general purpose motors, these motors may be arranged for side or inverted mounting and, in special cases, they may be mounted vertically. Figure 106 shows a motor of this class.

Railway Motors.—Railway type motors are designed especially for railway and traction service and are now little used for other applications. They are of enclosed design, due to their location under cars. Recent designs, however, are partially open, providing air circulation through the armature spider. Space limitations necessitate compact design. Frequent starting and acceleration demand series windings. Irregular duty

Fig. 107.—Railway motor.

dictates intermittent ratings. The high voltages used in railway work make necessary good commutating features and good insulation. The feature of portability requires elimination of excess weight. Figure 107 shows a railway motor.

The designation "mine type motor" is given to a special class of direct-current railway motors of particularly compact design for use on narrow-gauge mine locomotives.

Mill Motor.—Mill type motors are built primarily for service in steel mills and allied industries. They are used in these plants both for auxiliary drives on the mill machinery and for cranes, hoists, ore bridges and similar applications. They are designed particularly for rapid acceleration, quick stopping and frequent reversal of heavy loads, such service being typical with the manipulating drives in the mills. They are nearly always

under continuous manual or automatic control and are given intermittent service ratings. They are built standard with series or compound windings, the series field usually predominating in the compound motor. They are ordinarily totally enclosed because of their use in dirty and exposed locations. The frame is of cast steel, cylindrical in shape. In general dimensions they are longer and narrower than ordinary motors, the armature being long and of small diameter to aid quick acceleration and reversal. The frames are split horizontally to permit ready access to and removal of armatures, field poles and bearings. The upper frame casting is hinged on one side.

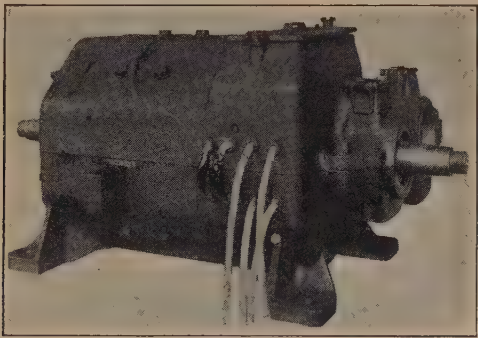

FIG. 108.—Mill type motor.

The field connections on the other side are made outside the frame so that they may be readily disconnected prior to opening the frame. Every provision is made for quick repair or exchange of parts primarily because of the seriousness of delays in mill applications and also because of use on cranes and in places difficult of access.

Mill motors are standard both with and without countershaft brackets, which, when supplied, form a part of the lower frame casting. Shaft extensions are provided at both ends of the motor for pinion, coupling or brake, when such is used. Tapered shaft extensions are provided to insure easy removal of pinions, together with a tight, true fit. Mill motors are provided with four wide spread feet which should afford sufficient room for both holding-down bolts and dowel pins. Figure 108 shows a mill type motor.

POLE PIECES

Materials and Construction.—The pole pieces of direct-current motors may be of solid steel or laminated construction. Laminated poles are preferable, as they permit higher flux densities and also reduce eddy current losses which occur in the pole faces due to flux pulsations incidental to armatures with wide slots, particularly with small air gaps.

Laminated poles are definitely uniform as against uncertain cast poles; they also permit greater accuracy in manufacture. The laminations in the pole pieces need not be as thin as those of the armature stacking, as the magnetism in the field poles does not reverse as does the armature flux. In some motors, notably those for elevator service, a short-circuited damping winding is sometimes introduced in the field pole faces. This causes the field circuit to build up or change values more slowly and insures more gradual acceleration and smoother speed changes.

Pole pieces should be bolted to the yoke, not cast in. With the latter construction there is always uncertainty as to the joint between pole pieces and yoke. Through the use of drilling jigs, bolted-in pole pieces may be spaced with great accuracy, whereas it is impossible for the molder to locate the pole pieces in the sand with similar precision. A great advantage of bolted-in pole pieces lies in the ability to remove individual poles and coils for repairs without removing the armature. Bolted-in pole pieces also have an advantage in flexibility, as they permit adjustment of the air gap by means of shims.

Interpole pieces are generally of solid steel but laminated construction is sometimes preferable, especially in the case of fluctuating loads.

THE ARMATURE

Armature Construction.—The armature of a direct-current motor is best made up by pressing onto the shaft a cast spider upon which are mounted both the armature stacking and the commutator bushing. With this construction it is possible to press the shaft in or out without disturbing the windings. In

the smaller sizes this construction may be supplanted by one in which the laminations are held firm by end rings, the commutator bushing being attached to one end ring to make stacking and commutator a unit. With this construction it is also possible to remove the shaft, leaving the working parts intact. The stacking is made up of soft iron laminations varnished to reduce eddy currents. Open slots are used in all but the smallest motors because this permits the use of form-wound, insulated and treated coils. It is well for the last few laminations on each end of the stacking to be of heavier stock than the rest, to prevent vibration. Fingers for buttressing the teeth should be attached to the end laminations. Ventilating ducts, if used, should be liberal to prevent clogging. If bands are used outside the stacking they should be recessed so as not to decrease the mechanical air gap and to prevent injury to such bands while inserting or removing the armature. Cast end plates, secured by ring keys, holding the stacking together, may well be designed to serve also as supports for the end connections. Oil-thrower discs are sometimes pressed onto the shaft outside the spider to prevent creepage onto commutator and windings.

THE COMMUTATOR

Commutator Construction.—This is a delicate device but a high degree of perfection has been attained in its manufacture. The segments should be of rolled or drawn copper, not cast. The mica segments should be of soft amber mica, finely split and cemented with a binder which will not disintegrate and pit. The segments should be of uniform thickness. Recent tendency is toward undercutting the mica in all cases where collection of dirt in the slots is not probable. This is done not only to prevent "high mica" troubles, but also to enable the use of brushes best suited in all features except that of mica abrasion. Undercut mica is particularly desirable in machines having many narrow commutator bars, where the mica represents a fair percentage of the total surface.

The mica V-rings should be made in one piece to lessen liability of grounds at the corner. Insulation should be provided between the bore of the commutator and the bushing.

It is well for the mica segments to extend beyond the copper at the inner end of the commutator to prevent leakage across bars at this point where dirt is likely to collect. The risers may be solid, the ends of the bars being slotted for the armature connecting leads, or open risers may be used. Open risers afford advantage in ventilation and involve less likelihood of breakage of the leads at the point of connection. Solder-throwing seldom occurs with open risers. Solid risers are commonly used for small armatures because cheaper to construct. Railway and mill type motors usually have solid risers to secure liberal commutator dimensions in connection with a narrow diameter armature.

WINDINGS

Armature Windings.—The armature windings of all but the smallest direct-current motors are assembled from coils formed and insulated before insertion. The span of the armature coils may be equal to or slightly more or less than the pole pitch. The latter type is termed a chorded winding and is used extensively in non-interpole machines, having the advantage that both sides of the coil are not in the neutral zone at the instant of commutation. The short-circuited coils may thus have corrective voltage generated in them to aid reversal of the current. Diamond coils, with modifications, are quite universally used in direct-current motors. Wave windings are employed ordinarily in all but the largest motors because this type of winding permits the use of fewer turns and larger size conductors. Coils may be made up of round wire, rectangular wire or strap copper. Rectangular wire has advantages over round wire in that less space is used for insulation, the coils hold shape better and the pressure is distributed. The thrust of the conductors in an armature is considerably more than is appreciated. Square wire has the advantage over odd rectangular shapes in that it is semi-standard and may be obtained readily for repairs. Double cotton covering is used for most armature conductors, the coil being taped and treated with varnishes. The coils of railway and mill type motors are generally insulated with built-up mica next to the coil, a cotton

tape being used on the outside to hold the mica in position. This is good construction, as the insulation next to the conductor is materially hotter than that next to the slot. The use of mica or asbestos insulation permits operation of the motors at higher temperatures and is particularly applicable to machines of the enclosed types. Armatures are ordinarily connected with a throw of half a pole span so that the brushes must be located opposite the center line of the poles. Some armatures are connected straight out, however, bringing the brushes opposite the interpolar position. Either bands or wedges may be used to retain the coils in the slots, although wedges are preferable, as they allow more ready access to individual coils for repairs. They also remove one source of grounds and short circuits, bands not infrequently cutting through the insulation and leading to trouble. Bands are universally used for retaining the end connections. No little thrust occurs in the end connections due to stray magnetism and they should be securely banded onto a supporting shelf to avoid movement and consequent chafing. Freedom and exposure for ventilation should be afforded so far as possible, however. In the larger machines, made-up bands are commonly used which are simply clamped together, permitting easy removal and replacement.

Field Windings.—The field coils of a motor are subjected to mechanical shock and vibration, magnetic thrust, repulsion and attraction between turns and expansion and contraction due to heating. They must therefore be tightly wound and securely fixed against all movement. They may be subjected not only to the normal impressed voltage, but to the high induced voltage or kick which occurs if the field circuit be opened suddenly. They must therefore be well insulated between terminals and between layers as well as from the pole pieces and frame. Shunt coils may be in circuit quite continuously so that heat dissipation requires attention. Space economy is a desirable feature, but undue crowding is to be distinctly avoided. Shunt coils for small machines are commonly wire wound under tension, cotton or enamel insulation being used. Rectangular wire is used for the larger machines, giving a better space factor and more rigid construction. The layers may well be

insulated from each other by paper strips. The end turns are retained by strips of tape or paper encircling them and in turn held under the central portions. The portions next to the pole pieces are insulated with pressboard, reinforced at the corners. The coils are frequently taped over all and treated, but, where construction permits, it is better to omit most of the outer taping to expose the surface of the coil more effectively for radiation. Field coils, more especially in the larger sizes, may be sectionalized, ventilating spaces being introduced between sections. The coil ends should be anchored within the coil and attached to flexible leads brought out for connections. Another good construction provides terminals attached to the anchored coil ends, jumpers being used to connect from coil to coil. Shunt field coils are usually treated by repeated varnish dips and baking, although the vacuum impregnating process is applied in some cases. Special treatments can be applied to motors to be exposed to moisture, chemicals and fumes.

Series and interpole-field coils of the larger machines are commonly constructed of strap copper wound on edge, insulated only by strips of paper or asbestos between turns and clamped in a pressboard spool. This is a solid and compact construction and an excellent one from the viewpoint of heat dissipation. In the smaller machines wire-wound coils, usually of square wire or flat strap, are used, the construction being similar to shunt coils. In some machines the interpole winding is concentrated in a short coil near the pole tip, instead of being distributed evenly along the entire pole piece. This is done in order to minimize magnetic leakage.

In some of the smaller compound-wound motors both the series and shunt turns are made up in a single coil. This practice is not to be commended, inasmuch as it introduces greater possibilities for electrical breakdown and renders repairs more difficult.

BRUSHHOLDERS AND BRUSHES

The box type of brushholder is now used almost universally for motors, although rocker type and reaction type holders are occasional. Reaction type holders require specially shaped

brushes. They are particularly good where very quiet operation is desired, as for elevator service in office buildings. The fit between box and brush with a box type holder must be snug to prevent rocking of the brush. Long boxes hold the brush steadier than short boxes. The springs should be designed to follow up wear without change in tension, and provision for adjusting the tension should be made. Both brushholders and tension springs should be protected against corrosion. Brass holders and bronze springs are better than steel. The brushholders of alternating-current motors should be made of non-magnetic materials. All brushes should be provided with shunts to avoid trouble at the sliding contact and to prevent current from heating the tension spring.

There should preferably be two or more brushes per stud and always more than two brushes per machine, except in fractional horsepower motors. Long studs should be braced at the outer end to secure rigidity and prevent chattering. The brushholders should be insulated from the frame through the use of porcelain, bakelite or similar material. Fiber has the bad property of expanding and contracting with moisture, ultimately loosening the joints. Provision should be made for shifting the brushes, preferably without disturbing the machine in operation. The brush yoke of interpole machines should be doweled, but chance for adjustment is desirable in case exchange of armatures or other cause makes some shifting necessary. Brushholders should be staggered in pairs to secure even wear and prevent grooving of the commutator.

The brushes in a motor must be suited to their work. The subject of brushes is too broad to be covered in a general discussion, demanding the consideration of many details.

BEARINGS

Sleeve Bearings.—The first requirement in bearings is liberal size. The bearings of small motors are usually held by end flanges or brackets attached to the yoke. The alignment being accurate, fixed sleeve bearings are permissible. For the larger motors pedestal type construction is generally

to be preferred. All pedestal type bearings may well be self-aligning and, preferably, split. The bearings of most small motors are of the solid sleeve type. It is desirable, and not uncommon, for the rear end flange to be split and equipped with a split bearing. This construction permits easy removal of the armature from the commutator end without removing pinion or coupling. In the larger motors of the self-contained type, split flanges and bearings for both ends are desirable. It is well for the bearings on both ends of the motor to be duplicates, thus reducing the spare parts item. Oil wells should be liberal to reduce attention and minimize troubles. Oil gages and effective means to prevent overfilling are important. Two oil rings per bearing introduce insurance against troubles due to a stuck ring. The end of the bearing housing should be closed by a cap to prevent entrance of dirt. Effective means, such as wiping washers, for prevention of oil leakage along the shaft into the machine, should be provided.

The solid sleeve bearings of small motors are usually of bronze, or special alloy, made in one piece. The larger split bearings are generally of the babbitted type, a cast-iron outer shell being used. Bronze is sometimes used for the outer sleeve to prevent injury to the shaft in case the babbitt melts and runs out.

Waste Packed Bearings.—Waste packed bearings are used in quite a number of motors, notably for the textile industry where the lint is prone to clog and cause seepage from oil-lubricated bearings. They are also supplied for the counter-shaft bearings of some motors.

Ball and Roller Bearings.—Ball or roller bearings appear to afford a number of advantages and their more general adoption is not improbable. Mention may be made of a few considerations involved.

Advantages.—The principal benefit afforded by ball and roller bearings arises from the fact that lubricant is effectively retained and does not work into the commutator and windings of the motor. Oil leakage from bearings is pronounced responsible for more than half our motor failures. Incidentally, the absence of oil drip may be of considerable import where cleanliness is necessary.

Ball and roller bearings require less attention than other types and they have been known to survive in spite of prolonged neglect.

The wear of these bearings, if of proper design, is very slight, so that renewals are infrequent. They also retain the rotor in central position and restrict vibration which may arise through excess bearing play.

Improvement in motor efficiency is a somewhat minor consideration. The gain is, in general, on the order of 1 per cent. It is greater for high-speed than for low-speed motors. Ball bearings are superior to roller bearings in this respect.

Ball and roller bearings are more compact than sleeve bearings. Motors so equipped are 15 to 20 per cent shorter in overall length than motors having sleeve bearings.

Where the oil may be siphoned out as by cotton mill lint or by windage of a blower, the use of ball bearings is advantageous. They are also useful for vertical motors or where the shaft may be inclined or where subject to pitching, as on shipboard.

Ball or roller bearings are used to advantage where it is desired to eliminate all end thrust, as for self-contained grinding wheel units.

Disadvantages.—A disadvantage of the ball or roller bearing is the difficulty connected with renewal and with the removal or interchange of rotors. These bearings cannot be split. The inner race must fit the shaft tightly and the bearing must be removed as a whole or dismantled in order to remove the rotor. The bearings may be exposed to dirt and damage while thus dismantled.

The refinement necessary in clearances and fits on the shaft and in the housing and the care necessary in the proper assembly, are handicaps. Workmen may need to be trained to handle these bearing types successfully.

Spare bearings of the sleeve type are relatively inexpensive. Babbitting may be quickly done where necessary. Loss of a ball bearing where no spare is available may be a serious matter.

There is some question as to the ability of ball bearings to withstand shocks successfully. The roller bearing is probably superior in this respect.

Some trouble has been caused by pitting due to acidity of lubricant. The grounding of armatures may cause pitting or burning due to current flow through the bearings.

Sleeve bearings are well established and are, in the main, quite satisfactory. Any change is undesirable unless fully warranted. The introduction of ball or roller bearings would involve considerable additional investment to motor manufacturers. Many users would be required to carry two sets of spare parts, at least during the transition period. The change involves expense which must be justified.

The cost of motors equipped with ball and roller bearings is somewhat higher than the cost of sleeve-bearing motors. If two types are manufactured, the cost of both will be enhanced. The increased motor cost due to ball or roller bearings is, in general, on the order of 3 to 5 per cent.

A number of methods have been developed or proposed for incorporating the ball or roller bearings. It may be in order to mention a few features which are desirable in the design:

Design Considerations.—The mounting arrangement should be such as to enable the armature to be removed without the necessity of removing the bearing from the shaft.

It should be possible to apply pressure to the inner race or sleeve so that the bearing may be removed from the shaft without transmitting end pull through the balls.

The bearing should be protected from dirt so far as possible.

To meet these requirements a construction is favored in which the bearing is enclosed in a separate housing, which fits into the bearing bracket but which may be removed intact.

The housing or container should afford sufficient space for lubricant. Provision should be made, usually in the form of labyrinth grooves, to retain the lubricant effectively. A non-acid grease lubricant is generally used for motors of moderate size and speed. This is less difficult to retain than oil. Oil may be necessary at high speeds.

Accurate machining of shaft and housing are necessary. The bearing should have a light drive fit on the shaft and should be held fixed, usually by a lock nut. The outer race should be a sucking fit in the housing and may be permitted to float. The inner race is sometimes mounted on a sleeve to distribute

the pressure over a longer length of shaft. This is not necessary except for severe duty.

Last, but not least, the bearings should be liberal in size. Considerable trouble may be attributed to lack of conservatism in bearing selection.

ALTERNATING-CURRENT MOTORS

The great majority of alternating-current motors are of the induction type. Induction motors are not as flexible as direct-current motors, and although widely used, the variety of applications is somewhat restricted by their lack of flexibility. Standard motors may be considered in four general classes,

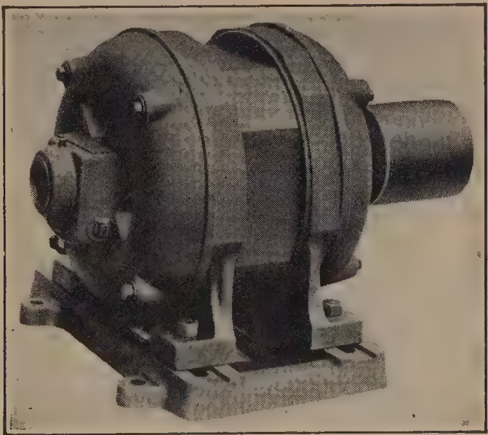

FIG. 109.—General purpose induction motor.

namely: commercial general purpose motors, crane and hoist motors, mine type motors and mill type motors.

General Purpose Motor.—The general purpose motor is a competitive design of light weight and open construction. Motors of this type may be obtained with either squirrel-cage or wound rotors. These motors are adapted and widely used for driving continuous running machines at fairly constant speeds. They are normally rated on a continuous duty basis.

The frame or stator of the ordinary induction motor comprises a skeleton ring containing the stacking for the primary

winding. The primary is nearly always located in the stator because of ease in introducing the primary current and because it carries the higher voltage winding which can thus be better insulated. The frame may entirely cover the stacking or may leave it exposed for radiation, the latter arrangement being preferable. The bearings in all but the largest motors are built in brackets attached to the frame. Provision is made in some motors for slight adjustment of the bearing brackets or of the bearings within the brackets to take up bearing wear and to maintain the air gap.

Magnetic Circuit.—The entire magnetic circuit of an induction motor must be finely laminated to reduce eddy current losses, as the magnetism is continually reversing. Ventilating ducts are not generally used in motors having narrow stackings, radiation being sufficient without them. In long cores, particularly in enclosed motors of the mill type, ventilating ducts aid in distributing the heating. End fingers should be provided to buttress the end laminations of the stacking to prevent chafing and noise.

Primary Windings.—The winding slots in the primary stacking may be of the open or partially closed type. Partially closed or overhung slots afford better distribution of the magnetic flux, reduce magnetic leakage and improve the characteristics of the motor. The use of overhung slots decreases the effective air gap by distributing the flux more uniformly. It also permits the reduction of the actual air gap, lowering the magnetizing current and improving the power factor. It is desirable for mechanical reasons, however, to have a liberal air gap, although this is attained through sacrifice in power factor. Open slots are not as desirable as overhung slots from the viewpoint of electrical design, but from a practical point of view they are to be preferred. With open slots the coils may be form-wound and treated before they are assembled, while with closed slots the conductors must be threaded in singly. Not only are better insulating methods possible with formed coils, but repairs may be made more readily. Formed coils are more firm and solid, may be better braced and are better heat conductors. In general, the advantages of formed coils in open slots more than offset the

disadvantages except, perhaps, in the very small sizes. The disadvantages of open slots are reduced in some designs through the use of magnetic wedges which produce an effect similar to that of overhung slots.

The primary coils, as above mentioned, may be either of the fully formed or of the threaded-in type. Diamond coils and basket coils are the types commonly employed for motors, basket coils being used only for small motors with overhung slots. Diamond coils may be used with either open or partially closed slots. They are easily manufactured and are suited to quantity production. Their symmetry and exact duplication result in electrically balanced windings.

The stators of ordinary induction motors are usually insulated with cotton, tape and other fibrous material of this class. Fully formed coils are thoroughly treated before assembling. Machines having threaded-in windings may have the entire stator subjected to the vacuum treatment if this is specified. This makes the windings solid and does away with air pockets and chafing spaces but renders repairs difficult. Special varnishes are available for application to the windings of induction motors where moisture or acid or alkali fumes may be encountered. This treatment is inexpensive and is to be recommended wherever conditions demand.

The span of the coils of induction motors is usually somewhat less than the pole pitch, since a gain is made through decreasing the end connections at slight reduction in the effectiveness of the turns. The windings are uniformly distributed and connected in groups with a number of coils per pole per phase. These groups are then connected in series or parallel and the terminals connected, in a three-phase machine, to make up a star or delta winding. It is usually possible to change the connections of the groups to adapt the motor for different voltages. In selecting a motor, it may be well to know for what voltages the machine may be adapted either for use in different plants or to make it suitable for the best local market as a second-hand machine. It is good practice to insulate the end coils of each group of coils with extra insulation, since the end coils of different phases are adjacent and are subjected to machine voltage. The terminal leads of the machine

should be anchored to the frame to avoid damage to the winding through pulling on the leads. The bearing brackets should be designed to protect the end connections from mechanical injury.

Rotor Construction.—The rotor of an induction motor should include a cast spider pressed onto the shaft, the stacking being mounted on the spider. The collector rings, when used, are generally mounted on a bushing pressed onto the shaft separately, and it is necessary to disconnect the rings to remove the shaft. The collector rings are sometimes mounted on a shaft extension and enclosed. Squirrel-cage rotors are very simple and rugged. Partially closed slots are generally used, the conductors being bars shoved through with the end rings connected to them. The conductor bars are ordinarily of copper. They may be round, square or of rectangular section. Deep rotor bars give high apparent resistance due to the reactance at starting, with the opposite effect near synchronism. They tend to increase the starting torque, but may also diminish the stalling torque.

The end rings may be of copper or of alloy having higher resistance. Rotors are built to have high or low resistance, depending upon the slip and torque characteristics desired. The number of end rings may be varied to secure the desired resistance. End rings are usually of disc form to secure stiffness, several rings sometimes being placed in multiple to provide heat-radiating area. In squirrel-cage motors most of the slip energy must be dissipated in the end rings. Fan blades are often provided to secure air circulation. Formerly most low resistance end rings were fastened to the rotor conductors by soldering with hard solder. This is not satisfactory, due to the tendency to unsolder with overloads. A bolted construction using spring washers to provide uniform contact is sometimes used for high resistance rings and has the advantage of withstanding high temperatures successfully. All methods of riveting have proved lacking, due to loosening caused by expansion and contraction. Most rotors are now brazed, welded or cast-welded, a very rugged and durable job resulting. Figure 110 shows an ingenious one-piece developed rotor winding recently adopted by one manufacturer. This

design eliminates all but two joints. Figure 111 shows a rotor design for small motors which employs a "cast-in" winding. End rings are sometimes supported by attaching to the rotor cores without insulation. Grounds have little influence in the ordinary squirrel-cage rotor, the secondary voltage being very low and the resistance of the iron circuit comparatively high so that little current is shunted from the short-circuited winding. The conductor bars may be insulated either with a paper cell or with a varnish before insertion in the core. In some cases the bars are inserted bare and the entire rotor surface is

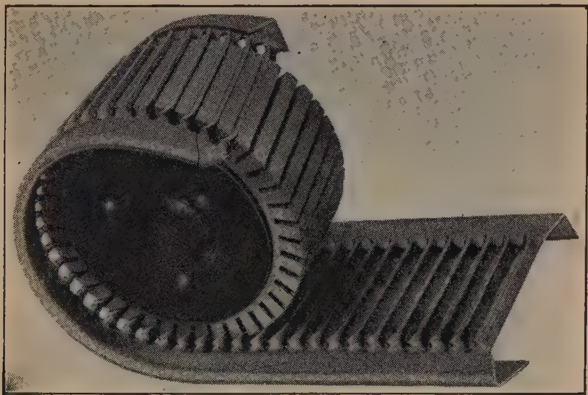

FIG. 110.—Developed one-piece rotor winding for squirrel-cage motor.

given a cement treatment after assembly, the cement penetrating and anchoring the bars firmly. In small squirrel-cage motors, it makes little difference whether the rotor bars are insulated or not. In large machines having appreciable voltage from one end of the bars to the other, local currents are set up through the stacking, reducing the starting torque but affecting running conditions little.

The stacking for wound-rotor motors is nearly always designed with partially closed slots and these are sometimes skewed to secure more quiet operation. Slot insulation is provided in the form of fish paper and treated cloth cells. The voltage of a wound-rotor circuit is comparable with that of the primary and the coils must be well insulated from each other

and from the core. The coils are usually of the diamond type, a wave winding being generally employed for convenience in connection. If made of wire they are threaded in one at a time. If made up of strap copper the conductors are insulated and inserted individually. Treated cotton tape is the usual conductor insulation, although sheet mica wrapped with cotton tape is used for severe service machines. If a motor is to be used for reversing duty or if plugging is to be expected, the rotor insulation must be especially good, since approximately double voltage will occur at the instant of reversal. After insertion

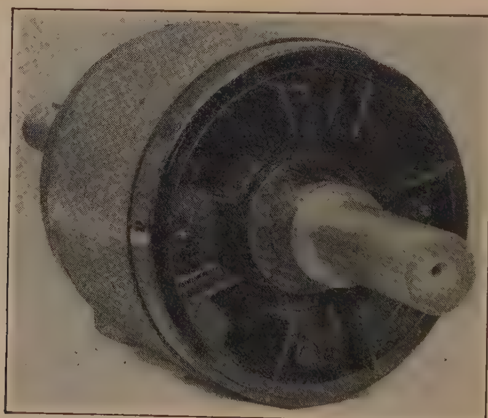

FIG. 111.—Squirrel-cage rotor with cast-in winding.

of the coils the cell insulation is folded over and wedges inserted. Bands are placed on the end connections, which should rest on shelves of the rotor spider. The bands and shelves should be arranged not to obstruct ventilation of the end connections more than necessary.

Rotor Connections.—Practically all wound rotors are connected three-phase, even though the primary winding is for a two-phase circuit. The primary and secondary windings are electrically independent, the magnetism maintaining relations between them, irrespective of their electrical connections, so long as the magnetic conditions are correct. Rotor windings are commonly star-connected, since this arrangement affords comparatively high voltage and low current in the external

circuit together with the minimum number of turns in the rotor winding.

Collector Rings and Brushes.—The collector rings may be of iron or bronze. Iron is quite satisfactory and, being cheaper, is generally used. The collector rings are preferably mounted inside the bearing bracket where protected. The brushes may be of copper gauze or carbon or metal-graphite, the latter being generally preferable. Box type holders are generally employed. There should be more than one brush per ring. Collector rings

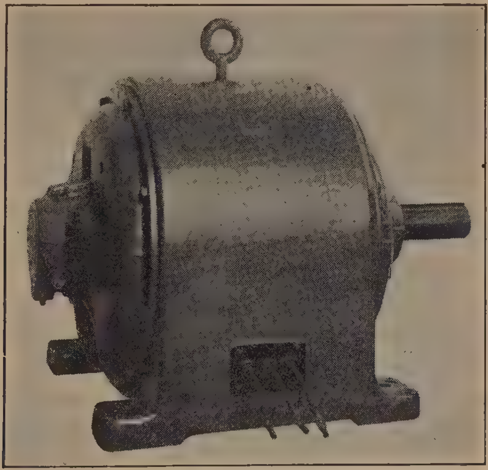

FIG. 112.—Mine type induction motor

should be liberally spaced, particularly in motors subjected to plugging.

Crane and Hoist Motor.—Crane and hoist motors are generally of the wound-rotor type. They are usually of the open type, sometimes nearly identical with the general utility design. They are rated on an intermittent duty basis. The rotors should be of small diameter and insulated for plugging. It is well to have the shafts extra strong and the rotor coils well braced. This service being quite severe, the construction should be sturdy throughout, little being compromised because of cost.

Mine Type Motor.—Mine type motors are fully enclosed, liberally rated and of generous mechanical proportions through-

out. They are provided with openings for ventilation and a fan is incorporated to cause air circulation. The brackets are horizontally split and the bearings also split to permit removal without disturbing the rotor. Pads are provided to which split bearing brackets for a counter-shaft may be attached. These motors are available in either squirrel-cage or wound-rotor type but are built in the lower speed ratings only. They are adapted, not only to mine service, but also for use in wet or dirty locations and wherever severe duty is the rule, as in steel mills, cement and rubber mills, coke plants, etc. Figure 112 shows a mine type induction motor.

Mill Type Motors.—Mill type motors are similar in external appearance, dimensions and design to their direct-current prototypes. They are not as extensively used as direct-current mill motors, due to their lesser flexibility and adaptability to control. They are totally enclosed. The rotors are long and narrow to reduce the inertia and permit rapid reversal. Wound rotors are used exclusively. The frames are split, as in direct-current mill motors, and the stator ring is fitted into the frame so that it can be lifted out with the rotor. High temperature insulations are used. The design is particularly rugged throughout. The general mechanical features are the same as in direct-current mill motors. This type of motor has been developed in 25-cycle ratings only.

VENTILATION

Disposition of Losses.—Losses are inevitably connected with the conversion of power from electrical to mechanical form. The heat arising due to losses originates at the point of loss. It is transferred and dissipated by radiation, convection and conduction. Most of the heat is conveyed from the point of origin to the point of dissipation by conduction. It is then carried away by radiation and convection.

Open vs. Closed Ratings.—In an open type motor large internal surfaces are exposed for radiation and convection. In a totally enclosed motor practically all the heat must be dissipated by radiation from the external surface. Enclosed motors are thus unable to dissipate losses to the same extent as open

motors, hence the losses must be restricted by working the materials easier at lower ratings.

Small motors have relatively large surface per unit volume. The possible rating is less affected by enclosure than in the case of larger motors. In general, however, the rating of a motor, when enclosed, is about half its open rating.

Methods of Cooling.—Temperatures in electrical apparatus are important as to maximum values because of the influence on insulating materials. Were copper and iron alone involved the allowable temperatures might be much higher than they are. Insulation is of equal importance throughout a machine. It is of little benefit to have one portion cool if damaging temperatures are reached at another point. Temperatures must be equalized, so far as possible, and hot spots avoided. To accomplish this it is desirable to provide for dissipation of heat at points near its origin. This minimizes the need of conduction, which necessitates heat gradient. Convection can be secured by directing air past the surfaces of a stationary part, for example, the cooling of field coils by the fanning action of armature rotation. Cooling may be obtained by movement of a body through the air, as in a revolving armature. Cooling may be provided by forcing air under pressure through definite paths and channels. Most machines combine all these methods but, in different types, different features predominate.

One kw. of energy will raise the temperature of 100 cu. ft. of air about 18° C. in 1 minute. With a given loss and a definite allowable temperature rise, a definite volume of air must be moved. This must be circulated in a manner to reach all ventilating surfaces and prevent hot zones. In an armature air may be brought along the shaft through an open spider, thence out through ducts in the laminations into the air gap. Dividing the stacking into sections makes it unnecessary for the heat to travel long distances across the laminations. The field coils of a direct-current motor, comprising many turns of insulated wire, tend to retain their heat. Field coils on the larger machines are usually arranged to be spaced out from the iron core to allow air passage under them. Not infrequently they are sectionalized and spacing strips inserted to give air access to interior surfaces.

The amount of ventilation required by a motor depends materially on its speed. A large, slow-speed machine has a lower output per pound of material and per square foot of radiating surface. At high speeds the rating increases and the output and losses are both enlarged. In large machines, open construction alone ordinarily suffices. In moderate speed machines, flat fan blades are frequently provided to stir up the air. In higher speed machines, pressure fans are frequently used in conjunction with enclosing end bells to cause forced air circulation through the ventilating ducts. Some machines are totally enclosed and supplied with either a self-contained or an external blower to supply air for ventilation. These types are particularly suited for dirty locations as clean air may be piped to the motors if necessary.

With improvements in design which overcome commutation and other difficulties, ratings are placed largely upon a heating basis and ventilation becomes a matter of increasing importance.

INSULATION

The three elements of an electrical machine are copper, iron and insulation. Copper and iron are active elements, while insulation is inert, but none the less important. The primary function of insulation is the electrical separation of conductors from each other and from the frame. Aside from this, insulation must be able to withstand mechanical stresses and to conduct heat away from interior points to surfaces where ventilation is possible. Unfortunately, poor electrical conductors are usually poor heat conductors, so that rapid transfer of heat is a problem without easy solution. Neither the iron nor the copper in a machine is seriously affected by temperatures such as are attained in electrical apparatus, nor is it greatly damaged by water, oil or dirt. Insulation is affected by all these things. Being thus the weakest link in respect to reliability, its importance cannot be overestimated.

Ohmic Resistance and Dielectric Strength.—Insulation enables a conductor to have a definite potential and enables adjacent conductors to have differing potentials. Because of the different potentials, current tends to leak slowly through

the insulation by paths offering even the slightest conductance. The ability to prevent this leakage may be termed ohmic resistance. If two conductors of different potential be placed adjacent to each other, but separated from one another, there is always a strain in the intervening space due to a tendency for the medium in that space to break down and allow current to arc across from one conductor to the other. The ability to prevent such disruptive discharge is called the dielectric strength of an insulator.

Insulating Materials.—Among the common materials entering into the insulation of electrical machines are: cotton, silk, paper, fullerboard, fiber, rubber, gums and resins, mica and asbestos. In general, the same kinds of insulating materials are used both for low voltage and for high voltage machines, the insulation being made heavier the greater the voltage to be withstood. In low voltage motors and generators the function is largely one of mechanical separation and insertion of ohmic resistance since the volt-withstanding ability is not severely tried. High-pressure machines, say above 6,600 volts, have their insulation proportioned more particularly with reference to its ability to withstand high tension.

All of the materials mentioned above, except mica and asbestos, are deteriorated by moderate heat. Cotton and silk are used largely because of their flexibility. Both are highly porous and absorbent and are intended essentially as mechanical separators, the interstices to be filled with varnish. Cotton insulation can be likened to lath or expanded metal and the varnish is comparable to the plaster or cement applied thereon. The varnish is most frequently applied after the tape is in place, although empire cloth and friction tape are types of preliminary filled insulation. Silk is much finer in texture than cotton, though more expensive. It is used where the space for insulation must be minimized. Silk is excellent for some repair work, since it affords better protection with less bulk than cotton. For instance, an abrasion on the portion of a formed coil which must be replaced in a slot can advantageously be taped up with silk, which affords a safe covering without bulging the coil. Paper is a comparatively good insulator; any close-grained grade, called fish paper, is commonly used. It is not flexible,

but is effectively used for straight runs such as cells for slots into which the coils are inserted. Paper also is often treated with varnishes, more frequently before insertion. Fiber is in reality paper stock formed into plates and tubes. It is used extensively for washers and bushings, but absorbs moisture readily. Rubber is not much used internally in electrical machines as it deteriorates under moderate temperatures. Molded insulations are used to some extent for accessories. Mica has high dielectric strength and is not deteriorated by such low temperatures, but it is inflexible and weak mechanically. It is prepared for use by forming ribbons or plates composed of mica flakes cemented to a thin, tough paper supporting medium by special binding gums. The most familiar use of mica is as micanite or micabond for commutator segment separation. Mica ribbon is quite commonly used for coil insulation where high temperatures are to be experienced. Motors in which high temperatures are necessary because of large outputs from small bulk such as enclosed motors for railway, haulage and mill service are types utilizing mica-insulated coils. Asbestos is a poor insulator in itself. It is porous, has comparatively low resistance, is bulky and weak mechanically. It is, however, largely unaffected by heat. Resins and gums serve a manifold purpose. They act as fillers to close all pores and spaces as with cotton insulation. In this way they form the real insulator, the cotton merely being the support. They also serve to conduct heat and to cushion against mechanical stresses. Moreover, by softening when heated, they tend to prevent the insulation from becoming dry and brittle at high temperatures. Varnishes are used to prevent water from entering and forming leakage paths. To do this they must either keep out the water entirely by closing all pores externally or they must form a solid impervious coating of the body of the varnish on the conductor itself inside the insulation. Spray application of varnish serves to coat the exterior and prevent entrance of moisture. Vacuum treatment endeavors to work the varnish in next to the conductor, forming a non-conducting layer and filling the pores as far as possible. Varnish reduces the extent to which moisture is absorbed, but it is unable to stop absorption altogether. Material which may in liquid

state fill the pores completely will fail to do so after drying by evaporation. Insufficient elasticity of the varnish is a fundamental defect, as it is unable to follow the expansions and contractions of the conductors sufficiently. Its continuity is therefore broken up and small crevices occur into which moisture can enter.

Mechanical Stresses.—The second important requirement of insulation is the ability to withstand mechanical stress. The conductors in a machine exert forces the magnitude of which are not often fully comprehended. Field coils tend to travel lengthwise along the pole pieces, while armature, stator and rotor conductors exert a pressure on the sides of their slots. The insulation must cushion the conductor, preventing vibration as far as possible. High-speed machines and those suddenly reversed, stopped and started, are particularly subject to damage. In railway motors mechanical vibration is ever present to cause deterioration of any insulation which is already brittle or which later becomes so, due to heat or long use. Movement of conductors must be restricted to a minimum by banding, wedging and bracing. Vibration causes cracking of the insulating filler or varnish. This destroys its continuity and paves the way for breakdown. An insulating covering which is full of small cracks and crevices has a dielectric strength little greater than air alone, since the opportunity arises for disruptive discharge across the air-filled breaks. Continuity of the surface is also important in preventing the absorption of moisture and dirt. After the exterior becomes cracked the insulation resistance is likely to be reduced.

Heat-resisting Qualities.—The third essential of good insulation is its ability to undergo fairly high temperatures without excessive deterioration. Insulation is the limiting consideration in rating a piece of electrical apparatus. The insulating materials most commonly used for motors will withstand a continuous temperature of 100 deg. Centigrade and afford comparatively long life. The life of an insulation not mistreated or subjected to undue moisture, oil or dirt, depends largely upon its temperature when in operation. It is found that intermittent loading and steady loads have about the same influence on insulation life, provided that the peaks are not of

such long duration that the machine becomes heated to a temperature corresponding to the extreme load. The temperature attained by an intermittently loaded machine is the same as that reached by the machine operating continuously for short periods. It is for this reason that haulage motors, elevator motors and such types are said to have 30, 40 or 60 minute ratings. This expression means that the machine, carrying full rated load for 30, 40 or 60 minutes, will reach the same temperature as will be reached when it is placed in its regular intermittent duty. These ratings are entirely empirical, based upon experience. Insulations have been developed to successfully stand temperatures up to 125 and 140 deg. Centigrade. These insulations use mica prepared in various ways, but it is commonly cemented to a paper binder as a supporting medium. This supporting material may deteriorate with heat without lessening the insulating qualities of the mica. The material is not strong and must be carefully braced to avoid vibration. Removal of coils for repairs, on which this insulation is used, is also attended with greater difficulties than where cotton tapes are used.

In some classes of apparatus there are certain definite points which are prone to attain higher temperatures than other portions. For example, that part of an armature coil which is embedded in the iron is much more likely to become overheated than are the end connections. The buried portion receives heat both from the copper and the iron while the ends must care for copper losses alone. Also better ventilation is possible for the end portions of the coils. It is therefore advisable to insulate the embedded straight portions of the coils, where little flexibility is required, with mica composite insulation. The ends may then be taped with treated cloth, without fear of injury from the lower temperatures occurring at these points.

As previously suggested, insulating materials are not good heat conductors. For illustration, the heat flow through a copper body is more than 2,000 times as rapid as the flow through tape. Iron is not nearly so good a conductor as copper, yet it conducts heat about 400 times more readily than insulation. Air is an exceptionally poor heat conductor and air pockets are therefore extremely undesirable in insulation.

It is good practice to make the insulation as thin, compact and dense as possible and to fill pores with varnish to make it solid. There is a great difference, for instance, between the temperature gradients of a vacuum-impregnated coil and one of cotton-covered wire externally varnished. Vacuum treatment is applied by first inserting the coil in a vat subjected to about 90 deg. heat and from which the air is exhausted. All moisture is easily vaporized under this condition. Then the gum preparation is pumped into the vat in a hot and fluid condition. It is sucked into the pores and, upon removal, bakes into a very solid unit.

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CHAPTER XI

THE PRINCIPLES OF DIRECT-CURRENT CONTROL

FUNCTIONS OF CONTROLLERS

One of the greatest advantages of electric motor drive rests in the ease, flexibility and accuracy with which motion, imparted by a motor, may be controlled. It is necessary that a motor be suited, in characteristics, to the nature of the load demand. It is of equal importance that the proper control functions be employed to direct the application of motive effort to greatest advantage.

Controller Functions.—An electric controller may be defined as a means for connecting and disconnecting a motor from its source of electric power and means for modifying electrical conditions to govern the performance of the motor.

The primary functions of a controller may be enumerated as follows:

To start and stop the motor, usually by connecting to and disconnecting from the source of power.
To govern the acceleration and deceleration of the motor and provide proper accelerating and decelerating conditions.
To control the direction of rotation.
To control the direction and amount of torque.
To control the flow of current.
To control the speed of rotation.
To protect operator, machinery, motor and controller.
To simplify and reduce the demands on the operator.

TO START AND ACCELERATE THE MOTOR

Need for Starting Devices.—Motors are designed with particular reference to running conditions. Controllers are depended upon to provide proper conditions during accelerating

and decelerating periods. They are somewhat analogous to the throttle valve of an engine or the clutch of a mechanical drive. The ohmic resistance of the armature of a direct-current motor is low. When the motor is at rest only the resistance of the armature circuit, including the series and interpole windings and series brake coil (if used), is available to restrict the flow of current. If full voltage were applied to this circuit, with the armature at rest, an excessive current inrush would result. To restrict the initial current it is necessary to increase the resistance of the armature circuit by introducing an external resistor. This resistor is given such a value that the total resistance in the armature circuit is sufficient to restrict the current inrush to a desired amount when full voltage is applied to the circuit.

As the armature accelerates, a voltage is generated within it due to movement of its conductors through the field flux. The value of this voltage depends upon the field strength and the armature speed. The direction of this counter-voltage is such as to oppose the impressed voltage. The net voltage available for driving current through the total resistance of the armature circuit (including the external resistor) is the difference between line volts and generated counter-volts. As the counter-voltage increases with the acceleration, the total resistance of the armature circuit may be reduced by diminishing the external resistor. As the armature approaches full speed, its counter-voltage becomes only slightly less than line voltage. The external resistor may then be eliminated as the resistance of the armature and series winding is then sufficient to restrict the flow of current resulting from the net voltage or difference between line volts and counter-volts.

Starting on Full Voltage.—Small direct-current motors, of fractional horsepower sizes, may be accelerated from rest without the use of external resistors. This is permissible because of their small size, limited current, low inertia and quick acceleration. Series- and compound-wound motors are best suited to this practice as the current inrush strengthens the field and causes the counter-voltage to build up rapidly.

Starting on Variable Voltage.—In a few special cases, motors are accelerated from rest by building up the impressed voltage

as the motor accelerates and builds up its counter-voltage. This is feasible only when the motor takes its power from an individual generator, as in some main reversing drives of steel mills and in mine hoist applications. This method has the advantage, with very large motors, of eliminating heavy starting resistors and switching equipment. In the great majority of direct-current starters and controllers, an accelerating resistor is supplied to restrict the current during the accelerating period.

TO CONTROL THE DIRECTION OF ROTATION

Reversing Requirements.—Many motors operate regularly in a single direction which is determined at the time of installation and there is no need for means in the controller to bring about reversal of rotation. Some motors operate ordinarily in a single direction but are occasionally required to reverse. A printing press drive is an example of this class. Some motors, such as those driving elevators and hoists, are required to operate in either direction at will. Some motors, such as those driving laundry washers and metal planers, must reverse repeatedly according to the cycle required by the driven machine.

Procedure.—To reverse the direction of rotation of a direct-current motor it is necessary to reverse the relative direction of flow of current in armature and fields. If the polarity of the fields be fixed, a reversal of armature current causes a reversal in direction of torque due to current in armature conductors reacting upon field flux.

In either a shunt or series motor is it possible to reverse rotation by reversing either armature or field. If the fields of a compound-wound motor be reversed, both series and shunt windings must be reversed in unison. It is therefore advisable and more common to reverse the armature connections to reverse rotation. In the case of interpole motors the interpole winding must be considered as part of the armature circuit.

Reversal of armature current is ordinarily brought about by reversing armature connections at the controller. In a few special cases, current is reversed by reversing the polarity of the generator which feeds the motor armature.

TO CONTROL THE DIRECTION AND AMOUNT OF MOTOR TORQUE

The direction of torque in a motor armature depends upon the relative direction of current flow in armature and fields. In the usual case, a motor revolves in the direction of its armature torque. When a motor rotates in opposition to its torque it becomes a generator. The torque may be in opposition to the rotation when a motor is "plugged," when dynamic braking is applied or when it is driven as a generator by an overhauling load.

Plugging.—If a motor be "plugged" by reversing armature connections quickly while running, the direction of the torque will immediately reverse but the rotation will not reverse until the reversed torque, plus the mechanical load, can overcome the inertia of the motor and driven machine, bringing the motor to rest. For a brief period the direction of motor torque is opposed to its direction of rotation.

Dynamic Braking.—If a rotating armature be disconnected from the line and short-circuited through an external resistor, at the same time maintaining the field flux, the voltage generated in the armature by rotation past the fields, will cause current to flow through the armature and the resistor short-circuiting it. This current will react with the field flux to produce a torque opposing rotation, the motor acting as a generator, the resistor being the load. This process results in a decelerating torque opposing rotation and is commonly termed "dynamic braking." The current for exciting the field coils of the motor may be taken from an external source or may be generated by the motor itself. Shunt, compound and series motors may all be arranged for dynamic braking. This subject is treated at some length in Chap. XXIII.

Overhauling Loads.—In the case of crane hoists and other overhauling loads, a condition arises where the motor torque may oppose rotation. An empty crane hook must be driven downwards against the friction of the hoisting gear. In lowering a heavy load, not only is the friction of the hoisting gear overcome but the load tends to speed up the motor, increasing

its counter-voltage above the impressed voltage. This causes the armature current flow to reverse, converting the motor into a generator, with torque opposing the rotation. If the motor pumps electric power back into the system, the term regenerative braking should be used. If the power generated in the motor is dissipated in resistors the term dynamic braking may be applied. This action is discussed further in Chap. XXIII.

Regeneration in Reversing Drives.—If a motor be fed from an individual generator and if the voltage of the generator be reduced below the counter-voltage developed by the motor, the latter becomes a generator and the current flow is reversed so long as the condition continues. This is one case of regenerative braking. It occurs only with reversing drives such as used in steel mills and for mine hoists.

Regeneration with Adjustable Speed Motors.—If an adjustable speed motor, operating at high speed with weakened field, have its field suddenly strengthened, the counter-voltage builds up and exceeds the impressed voltage and the current flow reverses, causing a regenerative braking influence which quickly slows down the motor. This action may be quite severe.

Control of Torque Value.—The amount of torque which a motor develops depends directly upon the magnetic field strength and the amount of armature current. In a shunt motor, having a nearly constant field flux, the torque developed is, within practical limits, proportional to the armature current. In a series- or compound-wound motor the torque increases in a somewhat faster proportion than the current. In any motor the torque can be governed by controlling either the field strength or the armature current. In the majority of cases the armature current is varied. In accelerating a motor, the armature current is limited, not only to protect the motor and the electric system but also to protect the driven machine against the sudden application of too high torques. In dynamic braking, the armature current is governed by adjustment of the resistor which short-circuits the armature. This controls the braking torque. In a crane hoist drive, the restricting torque in lowering is controlled by adjustment of both armature current

and field strength, all by means of resistors in the armature and field circuits.

Jam Resistors.—Sometimes motors are called upon to stand practically at rest and merely exert torque. In such cases the amount of torque developed and current passed are controlled by resistors which are then usually termed "jam resistors." The conditions here correspond to those existing when starting a motor from rest.

TO CONTROL THE AMOUNT OF CURRENT

Requirement of Resistance.—When a motor is in operation on full voltage, the current flow is determined primarily by the mechanical load demand. As already stated, when accelerating, plugging, retarding, braking, jamming and for other special purposes, resistors are used to introduce voltage drop and thus to restrict both current flow and torque production.

Determination of Accelerating Resistance.—The determination and layout of proper accelerating resistors involves many factors.

Three primary questions are involved, namely:

Total amount of resistance.
Subdivision into steps.
Current and thermal capacity.

Total Resistance Required.—The total accelerating resistance required depends primarily upon two factors, namely, the allowable current inrush and, where speed control by armature resistance is used, also the range of speeds desired. The current inrush permitted may be adapted to suit the starting load conditions. If a motor is to be started without load or with light load, a lesser current inrush will suffice than if heavy starting torque is demanded. The torque produced per ampere of starting current depends, to some extent, on the type and size of motor. In Table II are shown the peak torques developed by shunt, compound-wound and series motors (also wound-rotor induction motors) with several values of initial current inrush.

Having determined the initial current inrush to be permitted to develop the required starting torque, the total resistance to be inserted in the starting circuit may be calculated. Dividing the line voltage by the initial current inrush gives approximately the total resistance required in the armature circuit to restrict the current inrush to the selected value. The internal resistance of the motor and series brake circuits and that of the leads must be subtracted to determine the external resistance to be supplied. The reactance in the circuit also tends to decrease the current inrush to some extent. The total resistance, found by dividing the line voltage by the current inrush, may be decreased 10 to 20 per cent to allow for resistance and reactance of the motor and leads. The external resistor is thus determined.

If armature resistance speed control is desired, the speed range required may demand a higher value of armature circuit resistance than is needed to restrict the starting current and torque. The determination of resistors for speed control service is discussed in following paragraphs in this chapter.

Subdivision of Accelerating Resistors.—The general principle of accelerating resistor layout may be explained by reference to Fig. 113, which shows the general relations of current and speed in starting a direct-current shunt motor. The full-load current of the motor is I_1. We will assume that current peaks of 150 per cent full-load current are permissible and will determine I_2 accordingly. The total resistance of the armature circuit may be such that, in starting from rest, a current equal to I_2 flows. This amount of resistance gives armature regulation curve No. 1. As the motor accelerates, the current falls off along this curve until some point such as B is reached, where a block of resistance is cut out, again increasing the current to I_2. The motor then accelerates further until, at point D, further resistance may be cut out. This process is repeated until the external resistor is entirely cut out of the armature circuit and only the resistance of the motor and leads remains. The motor regulation curve No. 5 then results.

If the motor does not start on the first point, a current I_3, equal to approximately 200 per cent of full-load value, will be

taken when the first step of the resistor is short-circuited, as shown by point J. The dotted line KL shows that if the motor starts on the first point, but the first step is cut out before point B is reached, a higher current than I_2 will result.

This speed-current chart may be used to indicate how the resistor should be subdivided. Let R be the total calculated resistance and R_m be the allowance for resistance of motor and leads. R_x is then the external resistance required. This will be subdivided into steps R_1, R_2, R_3, R_4, as shown.

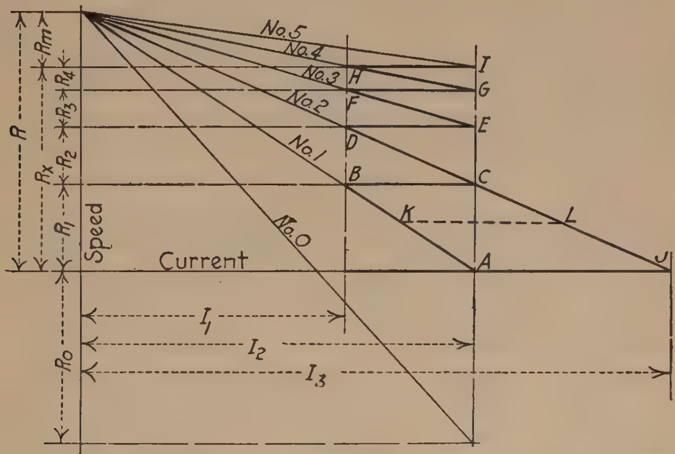


FIG. 113.—General relations of current and speed in starting a direct-current shunt motor.

It should be noted that the current intake decreases as the motor accelerates on any resistor step. The torque developed falls off roughly in like proportion. The minimum or valley current must be maintained more than sufficient to meet load torque requirements in order that acceleration may continue. The rate of acceleration will depend upon the difference between the torque developed by the motor, due to the current admitted, and the torque demanded by the frictional and work elements of the load, the marginal torque being available for acceleration.

If the load torque is heavy, and it is desired to minimize the peak currents, the range between peak and valley currents

will be small and a large number of steps will be required in the starting resistor. If a wide range is permissible, fewer steps will suffice.

The necessary or desirable degree of subdivision of the starting resistor depends upon many factors. The type of motor has a bearing; a series- or compound-wound motor needs fewer steps than a shunt motor because the current inrush on each step is partially restricted by a quick increase of counter-voltage due to increased field strength. The size of the motor is an important factor; the larger the motor the slower the acceleration, the more serious the current peaks and the more steps ordinarily desirable. The type of control has an influence; more steps are desirable for manual than for magnetic controllers as the accuracy of operation is less perfect and arcing more serious. The character of the load has a bearing in that a heavy load renders the use of more steps desirable. If a machine carries a flywheel or otherwise has high inertia, the accelerating load may be heavy, even though the friction and work load elements are small. If armature resistance speed control is desired, an additional number of operating points may be of advantage.

Having determined the permissible current peaks, represented by I_2, in Fig. 113, and the minimum or valley current necessary to overcome the load and provide for acceleration, the subdivision of the starting resistor to give a theoretical condition as shown in Fig. 113, can be computed, if desired. As previously explained, the total armature circuit resistance is evaluated to cause the current inrush I_2 when line voltage is impressed across this circuit. When the motor has accelerated to the point B on curve No. 1, the current I_1 is flowing. The counter-voltage at this instant is represented by the expression $\frac{I_2-I_1}{I_2} \times$ line volts. The resistor may now be decreased to such an extent that the total armature circuit resistance will pass the current I_2 when the line voltage minus the above-evaluated counter-voltage is impressed upon it. This method of calculation may be repeated to determine further steps until the accelerating resistor is entirely cut out. This method of calculation assumes a constant field strength.

With a series- or compound-wound motor the counter-voltage increases to some extent with the current inrush at each step due to the increase in field ampere-turns.

In view of the many factors influencing the subdivision of accelerating resistors, exact calculations are not ordinarily attempted. Operating conditions will vary from assumptions made for calculations and will vary from one time to another for a given installation. It is hardly feasible to subdivide accelerating resistors differently for each case. The practice has been fairly well standardized and subdivision is now based largely on tabulated values. Table I gives the number of resistor divisions which will apply in average cases for full-load starting duty where speed control is not required. This average practice may be departed from where conditions dictate.

TABLE I

Number of Resistor Divisions for Starting Direct-current Motors under Full Load

Manual control		Magnetic control		
Horsepower	All motors	Shunt motor	Compound motor	Series motor
5–10	4	2	2	2
15–25	4	3	2	2
30–45	4	4	3	2
50–75	7	4	3	3
80–125	7	5	4	3
135–275	9	6	4	4

An inspection of Fig. 113 shows that the resistor steps are unequal. The first step is comparatively large and succeeding steps decrease in size. Due to the several variable factors previously mentioned, it is customary to proportion resistor steps largely from tabulated data rather than to attempt calculation of each case.

Where speed control by armature resistance is desired the requirements for this purpose dictate, in a measure, the resistor step proportions. It is generally desirable to subdivide the

total speed range afforded into a number of increments or points. Sometimes it is desired that these increments be equal. More commonly they are made proportionate, so that near full speed the increments are small and become coarser as the speed range increases. The latter method of proportioning fits better the requirements of starting duty with the same resistor.

TABLE II

ELECTRIC POWER CLUB SERVICE CLASSIFICATION OF ACCELERATING RESISTORS

Starting torque in per cent of full-load torque					Resistor class numbers				
					Starting duty		Intermittent		
Per cent of full-load current on first point	Series motor	Compound motor, 30 per cent series	Shunt motor	Wound rotor induction motor	Light, 15 sec. in 4 min.	Heavy, 30 sec. in 4 min.	Light, 1 min. in 4 min.	Heavy, 2 min. in 4 min.	Continuous
25	8	12	25	. .	11	31	51	71	91
50	30	40	50	30	12	32	52	72	92
70	50	60	70	50	13	33	53	73	93
100	100	100	100	100	14	34	54	74	94
150	170	160	150	150	15	35	55	75	95
200	250	230	200	200	16	36	56	76	96

The load characteristic has a bearing. The load torque during acceleration may be constant, as in a line shaft drive, or it may increase with the speed, as in a fan or centrifugal pump application. If the torque increases with the speed the first resistor step may well be made relatively large and succeeding steps increasingly smaller, the taper being greater than in the case of a constant torque drive. This consideration applies especially to the subdivision of resistors for armature speed regulation duty for variable torque drives.

Due to the many elements involved somewhat different practices are followed by different manufacturers in the proportioning of accelerating resistors. Table III gives representative data for subdivision of accelerating resistors used either for starting or speed regulation duty with manual con-

TABLE III

PROPORTIONS OF ACCELERATING AND SPEED-REGULATING RESISTORS FOR USE WITH MANUAL STARTERS AND SPEED REGULATORS

Number of steps	4	5	5	6	6	7	7	8	8	9	9	10	10	11	11	12	12
Character of load, constant torque or varying with speed Step	Either	Constant	Varying	Constant	Varying	Constant	Varying	Constant	Varying	Constant	Varying	Constant	Varying	Constant	Varying	Constant	Varying
1	37	30	37	25.3	33.3	21.7	29.0	19.3	26.0	17.0	24.0	15.0	22.0	13.7	20.0	13.0	18.5
2	28	24	26	21.0	22.2	19.0	21.0	16.7	19.5	15.3	17.8	13.7	16.4	12.8	14.6	12.0	14.8
3	20	19	16	17.5	16.0	16.3	15.0	14.7	14.5	13.5	13.7	12.5	13.3	11.7	13.6	11.0	12.2
4	15	15	12	14.5	11.8	13.5	12.0	12.8	11.5	11.7	11.2	11.3	10.7	10.8	10.6	10.0	10.0
5		12	9	11.7	9.3	11.3	9.0	11.0	9.0	10.5	9.0	10.2	9.1	9.7	8.7	9.3	8.5
6				10.0	7.4	9.7	7.7	9.5	7.7	9.5	7.6	9.3	7.5	8.8	7.5	8.5	7.4
7						8.5	6.3	8.5	6.4	8.5	6.5	8.2	6.3	8.0	6.5	7.5	6.4
8								7.5	5.4	7.5	5.5	7.3	5.6	7.0	5.5	6.7	5.5
9										6.5	4.7	6.5	4.8	6.3	4.9	6.0	5.0
10												6.0	4.3	5.7	4.2	5.5	4.3
11														5.5	3.9	5.3	3.9
12																5.2	3.5

Tabulated figures show per cent of total resistance in each step.

trollers. Two methods of subdivision are shown, one suited for ordinary starting duty and for speed regulation with a constant torque load, the other for speed regulation with a load whose torque increases with the speed. Where used for speed regulation duty, the subdivisions shown give approximately proportionate, but not equal, speed increments. Table IV gives data representative of average practice in the subdivision of accelerating resistors used with magnetic controllers. It will be noted that the subdivision differs in the case of shunt and series motors.

TABLE IV

Proportions of Accelerating Resistors for Use with Magnetic Starters and Controllers

Number of steps	2		3		4		5		6	
Type of motor	Shunt	Series	Shunt	Series	Shunt	Series	Shunt	Series	Shunt	Series
Step 1	70	58	54	41	46	32	42	26	35	22
2	30	42	30	33	27	27	26	22	24	20
3			16	26	17	22	16	20	17	17
4					10	19	10	17	11	15
5							6	15	8	14
6									5	12

Tabulated figures show per cent of total resistance in each step.

Resistors for Plugging.—If the motor does not start from rest but is plugged, the maximum voltage across the armature and external resistor is the sum of the line voltage and the counter-voltage generated by the motor at the instant of reversal. In order to restrict the current flow with these combined voltages, an additional resistor R_o (Fig. 113) is required. The accelerating resistor R_x should be determined and divided in the prescribed manner. Resistor R_o should then be added, usually as a single additional step. The proper value of R_o can be determined by dividing the counter-voltage at the instant of reversal by the allowable current inrush. The value thus obtained may be discounted 15 to 25 per cent to allow for

resistance and reactance of leads and loss of speed at the instant of plugging.

Dynamic Braking Resistors.—The total value of armature circuit resistance to be used for dynamic braking may be determined by dividing the expected counter-voltage, based on speed and field strength at the time of reversal, by the permissible current peak in the dynamic braking circuit. The external resistor will be about 75 per cent of the value thus found. This resistor may or may not be subdivided. More commonly it is a single step. Two steps are frequently used with motors above 75 hp.

Current and Thermal Capacity.—Two resistors may be equal in ohmic value, yet one may have several times the weight of the other, the heavier unit being comprised of a greater length of larger section. The heavier unit will be able to absorb more heat and, having more area, can dissipate more heat with a given temperature rise.

Resistors for use with controllers have been classified as being adapted for light or heavy starting duty and intermittent or continuous speed regulating duty. A resistor having a given continuous rating in amperes capacity, may be given a higher capacity rating if the service is intermittent and a still higher rating if used only for starting duty. The ratings laid down by the Electric Power Club are based on a temperature rise not to exceed 250° C., under the stated conditions of service. The service corresponding to the classifications given are as follows:

Light-starting-duty resistors are designed to be in circuit not to exceed 15 seconds out of every 4 minutes with capacity load.

Heavy-starting-duty resistors are designed to be in circuit not to exceed 30 seconds out of every 4 minutes.

Speed-regulation light-intermittent-duty resistors are designed to be in circuit 1 minute out of every 4 minutes.

Speed-regulation heavy-intermittent-duty resistors are designed to be in circuit 2 minutes out of every 4 minutes.

Speed-regulation continuous-duty resistors are designed to be in circuit continuously.

Table II shows the Electric Power Club classification of resistors. Designating numbers are given the various resistor

combinations according to the total resistance and duty classification. Thus a class 74 resistor for a motor of stated horsepower at stated voltage will be designed to pass full-load current on the first point. This resistor may be used for speed regulation service if it is not in circuit to exceed 2 minutes out of each 4 minutes. It may also be used for starting duty but will be heavier than necessary for this service. The number of steps may be specified, otherwise the resistor will be subdivided by the manufacturer to suit the controller with which it is to be used.

This rather elaborate classification of resistors is desirable from the manufacturer's viewpoint. It tends, however, to a multiplicity of designs and a lack of standardization and duplication if resistors of all classes are used. It is the author's recommendation that the user select and standardize, as far as possible, one or two classes of resistors which are sufficiently heavy to meet his general requirements, such, for instance, as class 35 for starting duty and class 95 for speed control duty. The slight increase in first cost which may accrue from this practice is ordinarily warranted through advantages of interchangeability and duplication. The standardization of resistors has been carried still further in some large plants, to the extent of employing a few standard resistor units and connecting them variously to obtain required ohms and capacity. This is a highly commendable practice.

Accelerating resistors are usually so connected that they are all in circuit on the first step. The resistance is then reduced by short-circuiting the individual steps in sequence. In some cases, however, only a portion of the resistor is in circuit on the first step. The resistance is then reduced by cutting in additional resistors in parallel. In the first case the dissipating ability is reduced as the resistor is cut out. In the second case the dissipating ability is increased as additional resistors are cut in to bring the motor up to speed.

TO CONTROL THE SPEED OF ROTATION

Methods of Speed Control.—The speed of rotation of a direct-current motor depends upon the fact that the motor

endeavors to maintain definite relations between impressed armature volts and counter-volts. It is possible to govern the motor speed either by controlling the impressed armature volts or by adjusting the field strength to affect the counter-volts. The various methods of speed control are discussed in Chap. III. They may be briefly reviewed at this point.

ARMATURE VOLTAGE METHODS

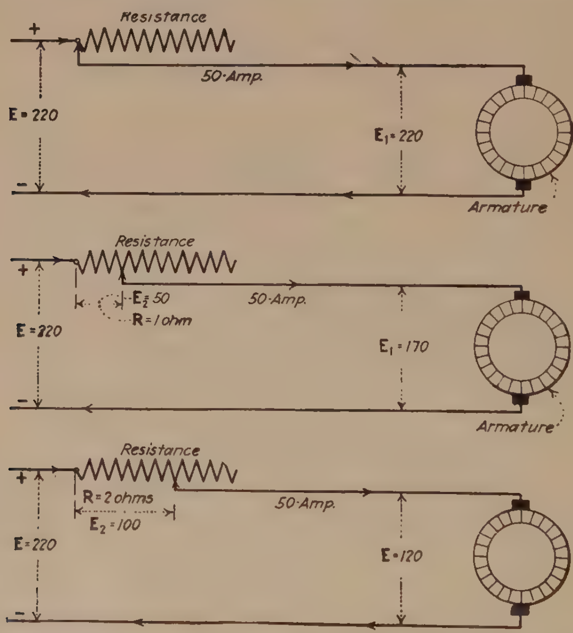
Multi-voltage System.—If circuits of different voltages are available, the armature may be supplied from more than one voltage. Other conditions being equal, the speed will be proportional to the impressed voltage. This is termed the multi-voltage system. It is not in extensive use.

Variable Voltage System.—The voltage of the generator supplying the motor armature may be varied. The motor speed will vary directly with the generator voltage, other conditions being equal. This method is possible only when the armature is supplied from an individual generator. It is used for a few special applications only.

Armature Resistance Control.—The speed of a direct-current motor may be reduced by decreasing the voltage impressed on the armature. When the impressed voltage is reduced the counter-voltage must drop to a like degree to maintain the current at a value necessary to carry the load. Figures 114, 115 and 116 show the relations existing in the circuit of an armature in series with a variable resistor. Consider a shunt motor connected to a machine requiring a constant torque at all loads, corresponding to 50 amp. armature current. With full voltage impressed as in Fig. 115, the motor will operate at full speed, say 1,200 r.p.m. If the controller is adjusted so that 1 ohm resistance is in series with the armature, as in Fig. 115, the voltage across the armature will be reduced by the amount of the drop in the resistor. This drop is equal to the resistance, 1 ohm, times the current, 50 amperes, and is 50 volts. The voltage at the armature terminals is $220-50=170$ volts. The speed will decrease to correspond to this voltage. The speed is directly proportional to the armature

voltage (with constant excitation); thus, speed $S=\frac{170}{220}\times 1{,}200$ $=927$ r.p.m.

If the resistance in series with the armature is increased to 2 ohms as in Fig. 116, then the drop through it will be 2×50 $=100$ volts. The voltage at the armature terminals will be



FIGS. 114–116.—Showing variation in voltage across an armature in series with a regulating resistor.

$220-100=120$ volts and the corresponding speed will be

$$S=\frac{120}{220}\times 1{,}200=654 \text{ r.p.m.}$$

In the first case the speed decreased from 1,200 to 927 r.p.m., or 273 r.p.m., in the second case from 1,200 to 654 r.p.m., a reduction of 546 r.p.m. or twice that in the first case. From this it is seen that where the torque remains constant, the speed decreases in proportion to the resistance in series with the armature.

If the torque is not constant the speed does not vary in proportion to the series resistance. At light loads there is little drop even with comparatively high resistance. For example, consider in Fig. 116 that the load is decreased to an extent such that only 10 amperes are required to drive the motor. Then the drop through the resistance is $2 \times 10 = 20$ volts, which leaves $220 - 20 = 200$ volts at the armature terminals. This will give a speed

$$S = \frac{200}{220} \times 1{,}200 = 1{,}091 \text{ r.p.m.}$$

From this it can be seen that this method affords little speed adjustment for light-load conditions. The heavier the load, the greater the speed range available.

Two general types of load must be considered in determining the resistance to be used for speed-regulating duty. The majority of drives have an approximately constant torque characteristic, and the horsepower increases with the speed. The amount of resistance to be used to obtain a given speed reduction may be determined by the formula:

$$R = P \times \frac{E}{I},$$

where R = total regulating resistance in ohms;
P = per cent speed reduction, decimal;
E = line voltage;
I = current to develop required torque.

This formula is based on the fact previously explained, namely, with a constant torque load, the reduction is proportional to the resistance.

The torque of fans, centrifugal pumps and some other machines increases with the speed. The friction load torque is about constant but the air or water delivery torque varies as the square of the speed and the horsepower varies approximately as the cube of the speed. In Fig. 117 curve A is a fan load characteristic, showing the relation between speed and current required. Curve B indicates the corresponding value

of armature resistance necessary to secure a desired speed reduction.

Suppose it is desired to obtain 50 per cent reduction in speed on the fan in Fig. 117. At 50 per cent speed, the current is only 40 per cent of full-load current. It is necessary to provide resistance sufficient to give the necessary voltage drop

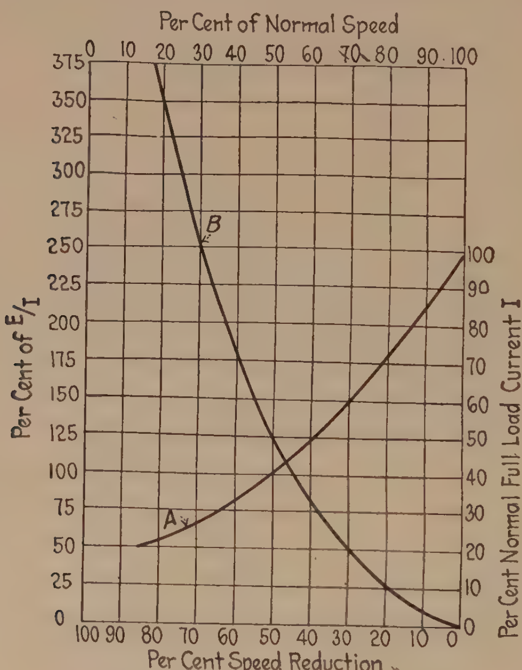


FIG. 117.—Curves showing relation of load current and armature regulating resistance to speed for a "fan-duty" or variable torque drive.

with this low current. The resistance in this case will be, approximately,

$$R=\frac{0.5E}{0.4I}=\frac{1.25E}{I},$$

where R = total regulating resistance in ohms;
E = line voltage;
I = current taken to develop torque required at full speed.

At 25 per cent reduction in speed the current is 65 per cent of full-load value and the resistance required,

$$R=\frac{0.25E}{0.65I}=\frac{0.38E}{I}.$$

Figure 117 may be used to determine approximately the amount of resistance necessary for any drive of " fan duty " characteristic, to give a desired speed reduction if the current I be taken as that required at full speed.

Since the current required by a " fan duty " load varies at different speeds, the current capacity of the different sections of the resistor may be proportioned accordingly.

The range of speeds afforded in any case by a given amount of total armature circuit resistance may be determined by the formula:

$$\text{Speed range in per cent}=\frac{T_1}{T_2}\times 100,$$

where T_1 = the actual torque demand at slowest speed, expressed in per cent of full-load torque:

T_2 = the peak torque developed by the inrush on the first point of the controller expressed in per cent of full-load torque.

Thus, if a shunt motor is provided with a resistor which will permit 150 per cent full-load current inrush and if the corresponding torque is 150 per cent of full-load torque and if the torque demanded at slowest speed is 60 per cent of full-load torque,

$$\text{Speed range}=\frac{60}{150}\times 100=40 \text{ per cent};$$

that is, this resistance will permit of armature speed control from 60 per cent speed to full speed. If a wider range is desired, the external resistance must be increased.

Armature Shunt Resistance Control.—Three limitations of speed control by resistance in series with the armature are: widely varying speeds with changing load, inability to reduce the speed with light loads and inability to secure stable low

speeds. These limitations may be materially alleviated through the use of a resistor shunting the armature in addition to that in series with it. Figure 118 illustrates this arrangement. Lower and more uniform speeds are obtained by this method than by simple armature resistance control due to the fact that the armature shunting resistor passes a current which increases the drop in the series resistor and causes a decreased voltage to be applied to the armature even when the load is light and the armature current small. A stabilizing influence is obtained because of the fact that, the higher the armature voltage, the greater the current carried by the shunting resistor, this current flowing through the series resistor tending to reduce the impressed armature voltage. A comparison

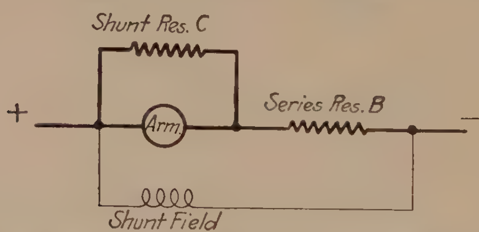


FIG. 118.—Shunt motor with armature series and shunt resistors.

with control by series resistance alone may be made through an example.

Consider a shunt motor having a full-load current of 50 amperes at 230 volts. Let resistor $B=3$ ohms and resistor $C=2$ ohms. If no armature shunt resistor is used, the drop across resistor B is 150 volts at full load and 15 volts when the load is 5 amp. The speed with 50 amp. load will be approximately $\frac{80}{230}$ of rated speed and at 5 amp. load it will be $\frac{215}{230}$ of rated speed. If the armature shunt is used, the calculations are as follows:

$$\text{Armature current} = I.$$

$$\text{Armature voltage} = E_a.$$

$$\text{Current through } C = \frac{E_a}{2}.$$

$$\text{Drop across } B=3\left(I+\frac{E_a}{2}\right).$$

$$E_a=230-3\left(I+\frac{E_a}{2}\right)$$

$$=\frac{2(230-2I)}{5}$$

Let $I=50$ amp.

$E_a=32$ volts.

Current through $C=\frac{E_a}{2}=16$ amp.

Current through $B=16+50=66$ amp.

$\text{Speed}=\frac{32}{230}$ (approx.) of rated speed.

Let $I=5$ amp.

$E_a=86$ volts.

Current through $C=\frac{E_a}{2}=43$ amp.

Current through $B=43+5=48$ amp.

$\text{Speed}=\frac{86}{230}$ (approx.) of rated speed.

It will be seen that the effect of the armature shunt is to reduce the speed at all loads and to make possible a considerable speed reduction even with light loads. This method of speed control is frequently applied for such installations as elevators and skip hoists where a slow speed, reasonably constant for all loads, is desired for a short period when approaching a landing so that accurate stops may be made. It is also used to secure low initial speeds for starting or adjusting machinery as for setting up a printing press or threading in a paper calender. The method is seldom applicable for continuous duty as the losses in the resistors are apt to be prohibitive. A controller utilizing this principle is described in Chap. XV, page 336, and in Chap. XXIII, page 473, the use of the armature shunt to obtain a braking effect is considered.

Series-parallel Control.—Two or more motors may be supplied for driving one machine. The motors are ordinarily duplicates and are similarly connected to the machine. If the armatures of these motors be connected in parallel across the line each motor will assume a portion of the load, operating at its corresponding speed. If the two armatures be connected in series the voltage across each armature is reduced. If there is no external resistance in the armature circuit then each armature has one-half line voltage across its terminals. The result is that the required counter-voltage is halved and the motor operates at half speed. A two to one speed range is thus seen to be possible with installations where two motors, mechanically connected, may be operated with their armatures connected either in series or in parallel. Many factors are involved in series and parallel operation of motors, these factors being considered more fully in Chap. XXI.

FIELD STRENGTH METHODS

If the field strength of a motor be changed, the counter-voltage generated at a given speed is immediately affected. Since the motor tends to maintain a balanced relation between impressed volts and counter-volts it follows that a change in field strength brings about a change in speed sufficient to re-establish the balanced condition. Weakening the field of a motor tends to reduce the counter-voltage and thus forces the motor to speed up. Strengthening the field has the opposite effect.

Shunt Field Resistance Control.—The most common field control application is the adjustable speed motor. The motor is designed to operate at its minimum rated speed with the shunt field connected across the line. The shunt field is weakened by the insertion of resistance in series with it. At any given position of the field rheostat the motor speed remains nearly constant, regardless of the load. The range of speed control depends upon the design of the motor. Almost any well-designed shunt interpole motor will permit an increase of 15 to 25 per cent above normal rated speed. Adjustable speed motors are standard for ranges up to 4 to 1. Special motors

are sometimes built having as high as 6 to 1 ratio. In applying this method care must be exercised to ascertain that the maximum safe speed of the driven machine is not exceeded. It is not always necessary to employ the full possible speed range of a given motor. The amount of resistance in the field rheostat can be arranged to give any range within the limits of the motor's rating.

Starting an Adjustable Speed Motor.—If an adjustable speed motor be started with weakened field the torque developed per ampere input into the armature is relatively low. As a result, the motor may be unable to start with normal current input and, in any case, the acceleration will be slow. If the accelerating resistor is cut out, either manually or by a time element controller, at the usual rate, excessive currents will flow due to the slow acceleration and the deficiency in counter-voltage developed. For the reasons above stated an adjustable speed motor should always be started with the shunt field fully excited. Provision is made in most controllers to insure this condition.

Predetermined Speed Control.—It is very often desired to set the field rheostat of an adjustable speed motor to give a speed best suited to the work in hand. It is further desirable to then be able to start and stop the motor without the necessity of readjusting the rheostat each time. To make this possible, many controllers are arranged with a relay which functions to short-circuit the field rheostat while starting and then to introduce it after the accelerating resistor is cut out. Such a controller is said to afford predetermined speed control.

Field Control with Series Motors.—It is not possible to adjust the field strength of a series motor independently by means of series resistors. If a resistor be connected around the series field of a series motor it will divert from that field some of the current which it would otherwise normally carry. The effect is to weaken the field and increase the speed. This method is not extensively used but it is sometimes employed to secure a high-speed operating point in crane hoist controllers. The shunting resistor and its connecting leads must be of very low ohmic value.

The armature shunt, previously mentioned in connection

with shunt motors, may also be employed with series motors. If the shunting resistor is connected around the armature only, both the armature current and the shunt resistor current pass through the series field of the motor. The influence of the shunt resistor is thus twofold. It increases the series field excitation at all loads, the effect being most pronounced at light loads. It has an effect equivalent to the addition of shunt ampere-turns to the field winding and tends to give the motor a compound characteristic. The use of an armature shunt resistor with a series motor has an effect similar to that obtained with a shunt motor but in a greater degree. The heating of the series field windings due to increased current places limitations on this practice.

Crane Hoist Control.—Series motors are commonly employed for "dynamic lowering" with crane hoist controllers.

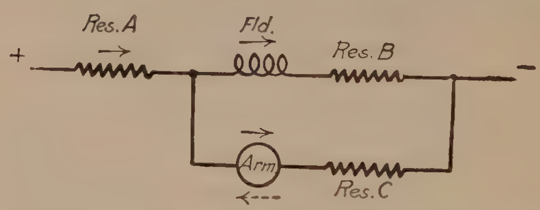


FIG. 119.—Lowering connections of a crane hoist controller.

When hoisting, the motor is connected in a normal manner with the armature, series field, series brake coil and accelerating resistor all connected in series. The connections for lowering are such as practically to convert the series field into a shunt field by placing it across the line in series with resistors. Figure 119 shows the lowering connections of a typical hoist controller. The motor is operative with either a positive or negative load. If the load is positive, the motor will drive the hoist downwards and current will flow in the direction indicated by the arrows. If the weight handled is just sufficient to overcome the friction of the hoist, the load is zero, no current flows through the armature but the field is excited. With an overhauling load, the armature current is reversed, as indicated by the dotted arrow, but the field current continues in the same

direction. The speed can be controlled by varying the series field current by varying the resistors A and B in series therewith, or by changing the resistor C in series with the armature. The resistor C reduces the speed as a motor and increases the speed as a generator when the load overhauls. When operating as a motor the counter-voltage plus the drop in resistors A and C equals line voltage; the resistors decrease the speed. When operating as a generator the resistance drop in the armature circuit increases the counter-voltage which must be developed to cause the flow of armature current necessary to produce the required restraining torque, hence increases the speed. A controller of this type is described and discussed more at length in Chapter XV, page 344.

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CHAPTER XII

PROTECTIVE FEATURES OF CONTROLLERS

The first function of a controller is to make possible the effective use of a motor. The second function is to protect against damage and abuse. Protective features are in the nature of additions or ramifications upon the elementary needs for the purpose of extending the service which the control may perform.

Overload Protection.—Motors are constructed in various sizes and types, each having limitations in its ability to convert electrical into mechanical energy. These motors are ordinarily connected to systems which can supply electric energy far beyond that which the motor can convert. The machinery which is driven by a given motor is designed with ability to transmit the amount of mechanical effort which that motor should properly supply. A great excess of electrical input into a motor will damage the motor, by burning at contacts or by overheating. An excess of mechanical output may damage either the windings or mechanical parts of a motor due to the excessive stresses. It may also damage the driven machinery for like cause. The rating of a motor is a nominal matter. Most motors can and will convert energy much in excess of their rating. In order to prevent damage to both motors and driven machines some means is desirable to limit the electrical input and mechanical output. This may be done either by disconnecting the motor entirely from its source of electric power or by modifying conditions to decrease the load. The more common procedure is to open the motor circuit when the load exceeds the safe prescribed value.

Momentary and Sustained Overloads.—Momentary extreme loads may damage a motor either by flashing or by excess mechanical stresses. A motor may also be damaged by sustained overloads which are insufficient to damage it except by

heating. It is desirable to permit moderate overloads to be carried for short intervals but to prevent their continuance to an extent sufficient to overheat the motor. This is ordinarily accomplished by use of a protective device having a time lag sufficient to prevent operation on momentary peaks, yet operative under sustained overloads.

Methods of Overload Protection.—The most common overload protective devices are fuses, circuit-breakers and overload relays, the latter being used in conjunction with contactors or switches.

Fuses.—Fuses are relatively cheap in first cost. Renewal costs may be high if fluctuating loads or other conditions render frequent renewal necessary. They have but a slight time element. They are not always accurate as to calibration. They are liable to substitution and overfusing by operators and such practices are not readily detected. The difficulty in locating a blown fuse and the delays incident to renewal are often disadvantageous. Their renewal is fraught with some danger.

Circuit-breakers.—Circuit-breakers have the advantage of low maintenance cost, quick indication of opening and quick reset. They are supposedly accurate of calibration but not always so. They afford a considerable range of setting and indicate the setting in use. Circuit-breakers of the air-break type are commonly used for direct-current work and to some extent for alternating-current service, particularly in the smaller sizes. Oil circuit-breakers are used for the more severe alternating-current duty.

Overload Relays.—These are devices which serve to make or break a pilot circuit which, in turn, causes the opening (or closing) of circuit-breakers or magnetic contactors. These relays are generally magnetically operated by a series coil which is connected in the motor circuit directly or through current transformers. These relays are subject to calibration over a fairly wide range. They are commonly of the solenoid and plunger type. Calibration is obtained by adjustment of the position of the plunger.

Overload relays may be equipped with series coils only or series and shunt coils may be provided. When series coils only are provided, the relay will hold open only while the cur-

rent flow in the series coil continues, unless a catch is supplied. Where both series and shunt coils are supplied, the series coil acts to open the relay and the shunt coil then suffices to hold it open so long as the current continues in the shunt coil.

Time Element Feature.—Overload relays may be instantaneous in their action or a time element may be introduced. The relay shown in Fig. 120 is an instantaneous trip relay while that shown in Fig. 121 has a time element feature. The instantaneous trip relay protects effectively against short circuits,

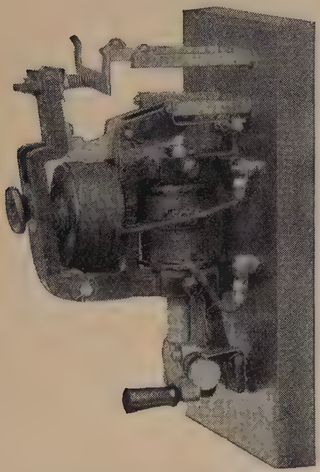

Fig. 120.—Instantaneous trip, magnetic reset direct-current overload relay.

Fig. 121.—Time element trip, magnetic reset direct-current overload relay.

grounds and similar severe conditions but will not always protect against sustained moderate overloads because it is usually necessary to set an instantaneous trip relay or circuit-breaker rather high to prevent tripping on fluctuations or peaks of short duration. The time element feature enables a relay or breaker to be set at a value sufficiently low to protect a motor or line from injury due to sustained overloads, at the same time permitting short peaks without tripping. This feature is particularly desirable where fluctuating loads are involved. It is useful for overload protection of squirrel-cage induction motors,

as the setting may be made such as to protect the motor while running, yet hold in during the brief peaks incident to starting.

The time element feature is ordinarily obtained through use of an air or oil dash-pot. With air dash-pots very close fits are required and the air discharge opening must be very small, making accurate adjustment and maintenance of calibration difficult. In some air-delayed relays a diaphragm is used rather than a dash pot. The time element is obtained by causing the bellows-like diaphragm structure to force air through a restricted opening. This design eliminates difficulties due to the close piston fits necessary in an air dash-pot. Oil dash-pots are more generally used. One drawback is the change of viscosity of oil with changes of temperature. Special oils are available which minimize this disadvantage but they do not entirely eliminate it. It has been the writer's experience that those dash pots are most reliable which use fairly heavy oil and a rather large opening through the piston. These are not seriously affected by dirt or by variations of piston clearance. Time element overload relays ordinarily have an inverse time action requiring little time to open under a short circuit but acting rather slowly under a moderate overload.

Reset.—Overload relays may be further described as

Instantaneous reset;
Automatic reset;
Hand reset.

The instantaneous reset relay closes at once when the current in its operating coil falls. The automatic reset relay, once opened, remains open until reset, either by opening its shunt-coil circuit, if of that type, or by energizing a reset magnet which trips the catch which holds the relay open. Hand reset relays, once open, remain open until reset by hand. Each type finds applications according to the conditions to be met.

Since overload relays ordinarily function only at infrequent intervals they are more liable than contactors to collect dirt and corrode and they may well be enclosed. Enclosure also discourages tampering to some extent. The prevention of tampering with overload relays is sometimes a rather difficult matter.

Overload relays for use on alternating-current circuits are further described in Chap. XVIII, pages 406–407.

Other Devices.—There are several devices, aside from fuses, which depend on the heating action of currents for their operation. One of these is the protective plug shown in Fig. 122. This plug has a heating coil within the cylindrical unit. The heating coil melts the fusible link above it and permits a flat spring contact arm to fly to the dotted position indicated, thus interrupting the motor circuit. This device is used for small induction motors only.

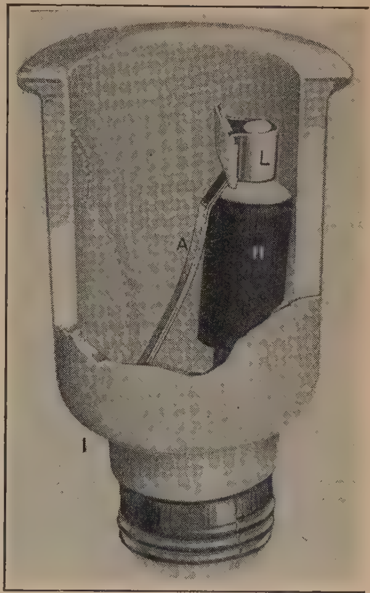

FIG. 122.—Fusible protective plug for small induction motors.

In another device an alloy wire under tension elongates sufficiently due to heat to permit closure of a pilot contact. In another device the overload relay coil is bridged around an alloy shunt. When this shunt heats sufficiently, its resistance increases to a point where most of the current passes through the relay coil, causing it to operate. A device known as a mercury overload relay is shown in Fig. 123. Current passing through a heating coil surrounding a tube containing mercury causes a part of the mercury column to vaporize and thus open a pilot circuit. All these devices based on heating effect have a time delay feature due to thermal capacity.

Thermal Relay.—The time delay obtained in the operation of overload protective devices, through the use of dash pots and most thermal devices, is but a few seconds. A motor can successfully withstand a moderate overload for a much longer time. It would be desirable to have a time delay of 10 to 30

minutes which would permit the motor to develop its full possibilities when called upon. Such devices are now becoming available.

An oil-immersed thermal relay which affords a long time delay and protects approximately in accord with motor temperature is shown in Fig. 124. This relay contains a heat-sensitive element of thermostatic metal, immersed in oil. This element carries the current and the oil serves to absorb the heat

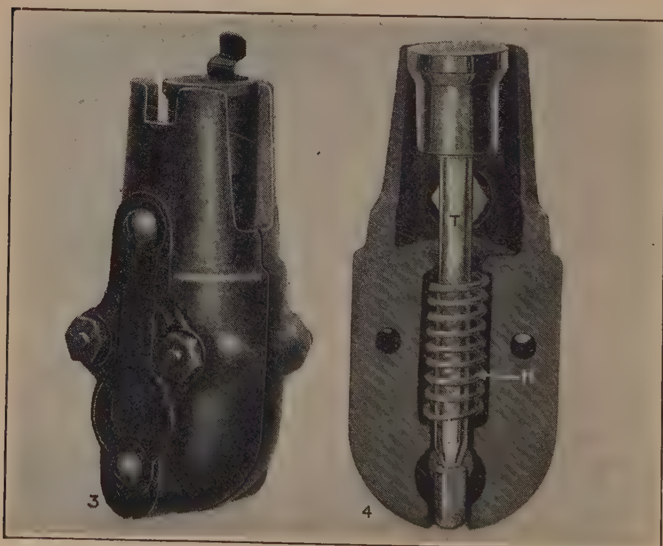

FIG. 123.—Mercury column overload relay.

generated, approximating the storage of heat by the motor mass. The heat-sensitive element actuates a dial indicating the temperature condition of the relay and thus the approximate temperature of the apparatus. It also serves to open or close pilot contacts. This type of relay is intended for use particularly in connection with large motors and apparatus.

Degree of Protection.—A motor which is not overloaded may be damaged by burning or overheating resulting from insulation failures or accidental contacts which short-circuit portions of the windings. If these faults are such as to cause

excessive current intake from the power lines, the overload protection serves also as a means to limit the damage resulting from the fault. Some faults, such as a short-circuited armature coil, may not cause the protective devices to operate as excessive currents are local to the faulty coil and do not pass through the protective devices.

If a motor is operated on a circuit which is either normally or accidentally grounded, a ground in the motor or controller may cause a short-circuit or some important portion of the circuit may be "shunted" or bridged around by the ground. The protective devices may serve to afford a measure of protection against grounds, their efficacy depending largely upon their character and their location in the circuit.

Fig. 124.—Thermal relay, oil-immersed type.

Location of Protective Devices.—In order to protect a direct-current motor fully, it is desirable to install fuses or other circuit-opening devices in both positive and negative lines. If circuit-breakers are used, they may best be made double-pole. If two trip coils are installed, one on each side of the line, the protection is quite complete. Where contactors are employed as circuit-breakers, two overload relays or one double coil overload relay may well be used. Sometimes one relay is of the instant trip type, giving short-circuit protection, while the other has a time element to afford overload protection. This is a good arrangement.

Under-voltage Protection.—It has been previously set forth that large motors of any type should not be started from rest by connecting them directly across the power lines, it being necessary to modify the electrical conditions during the accelerating period. When a motor is running, its controller is nor-

mally in the "on" position. If the power is interrupted and again established before the controller is returned to its "off" position, damage may result to motor, controller or machine. To prevent this occurrence most controllers are provided with a "no-voltage release" feature which causes the controller to return to "off" position when the circuit is interrupted or when the voltage falls to a low value.

If an automatic controller is equipped with a "no-voltage release" feature, it will return to "off" position upon interruption of power. If the master switch remains "on" the controller will again start the motor upon return of power, the starting operation being normal. This is a desirable feature for many installations such as fans and pumps. It is undesirable in cases where a workman might be working on a machine automatically starting as above described, or where automatic starting of a machine unobserved may be dangerous or undesirable. To prevent accidents from this cause many automatic controllers are equipped with a "no-voltage protection" feature. This is similar in action to the "no-voltage release" except that the controller will not automatically start the motor upon return of power after an interruption, it being necessary for the operator to manipulate his controller to accomplish this.

Time Element Feature.—It is sometimes quite undesirable that a motor be shut down due to low voltage unless entirely necessary. In order to prevent operation of under-voltage devices due to momentary drop of voltage a time delay feature is occasionally included.

Phase-failure Protection.—In the case of polyphase alternating current motors it is desirable to protect against operation "single phase." Such a condition may readily arise due to blowing of one fuse or faulty contact in one circuit of a controller. A polyphase motor will not start single phase but will continue to run if already under way. Its capacity is materially reduced and it will generally overheat if called upon to deliver its full mechanical output. The current taken from the remaining phases is increased and a measure of protection is afforded by the overload devices in these circuits but, if these are not set sufficiently low, overheating is liable. Many motor burnouts are attributable to single-phase operation.

Voltage Relays.—It is difficult to protect against single-phase operation through use of voltage relays as the voltage is maintained across the open phase due to induction generator action of the motor. The use of under-voltage relays in two phases will protect in a measure against attempting to start with a phase open. Starting devices having a double-throw feature may permit a motor to start polyphase but the running position may have a faulty contact or a blown fuse, causing the motor to run single phase. Voltage relays do not protect against this contingency.

The need of a phase failure protective device which will protect against continued single-phase operation of a running motor has caused the recent introduction of relays to fulfil this requirement. One device of this type operates on the induction principle in which a revolving field causes a disc to rotate through an angle in much the same manner that an integrating wattmeter disc is rotated. Coils connected in series with the motor, directly or through current transformers, are wound on cores provided with shading coils so that, individually, they set up a counter-clockwise torque which tends to rotate the disc and thus to open the contacts in a pilot circuit. Acting in combination, when polyphase power is flowing, these coils set up a revolving field which overpowers the single-phase action and causes the disc to rotate in a clockwise direction and close its contacts. When power is cut off all phases, the contacts remain closed but if one phase only of the motor opens, the polyphase action is lost and the single-phase action causes the relay to open its contacts and thus cause the motor to be disconnected. This single-phase action is not effective on very light loads but is effective on loads sufficient to cause possible injury to the motor.

Phase-rotation Protection.—In some cases, as in elevator and hoist service, it is advisable to protect against the possibility of a reversal of primary phase relations which would cause reversal of rotation of the motor. Relays are available which afford protection against this contingency. Some of these operate on a wattmeter or induction principle wherein a torque rotates a movable element to make and maintain a contact. Reversal of phase reverses the torque and opens the con-

tact. Figure 125 shows a relay of this type. The phase-failure relay above described is of this general description and is also effective as a phase-rotation relay.

Other devices combine two voltage relays which function on the basis of different voltages resulting from different phase relations. The connections for a device of the latter type are shown in Fig. 126. Relay *B* is connected across one phase.

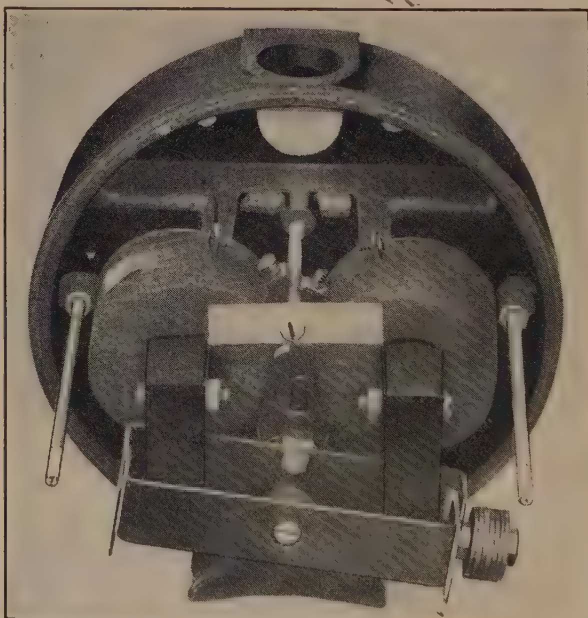

FIG. 125.—Combination phase-failure and phase-reversal relay that operates on the principle of an induction-type wattmeter.

The coil of relay *A* is connected to one phase lead and to the junction of a resistance and a reactance. When phase relations are correct, the two component currents through the relay coil are cumulative and the relay closes. When a phase is reversed, the component currents are opposed and the relay remains open.

Shunt Field Relay.—If the shunt field circuit of a direct-current motor becomes de-energized, the motor loses most of

its counter-voltage and tends to greatly increase its speed. The armature current ordinarily increases to a point where the overload relays might trip but, particularly if they are of the time element type, the action is delayed and the motor may reach a damaging speed. To safeguard against this contingency a relay is sometimes inserted in series with the shunt field so that, in case of open field circuit, the relay will open and cause the circuit-breaker or line contactors to disconnect the motor. This type of relay is particularly applicable to adjustable speed motors due to the likelihood of open circuits in the field rheostat. It is somewhat difficult to obtain a relay which

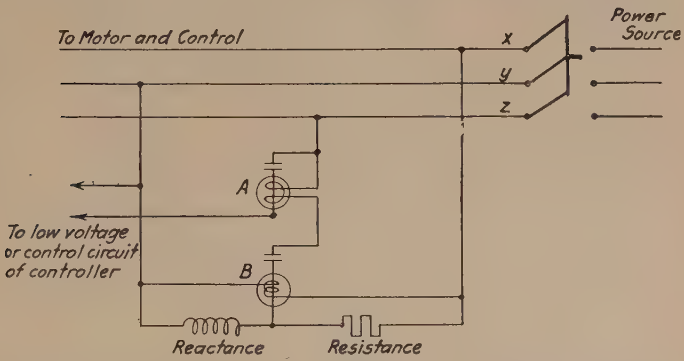

Fig. 126.—Combination of two voltage relays to afford under-voltage and phase-rotation protection.

will be effective over a wide range of field current values such as may exist with an adjustable speed motor. Moreover, transformer action between armature and fields may cause momentary drop in field current due to fluctuations in armature load. Damping devices may be necessary to overcome this difficulty.

Limit Switches.—In the case of many driven machines a travel occurs, the permissible travel being limited. It is not always safe or may not be desirable to expect the operator always to stop the machine within the safe limits of travel. In such cases it is customary to provide a "limit switch" which is a means for automatically stopping the motor before the limits of travel are exceeded. Limit switches may interrupt or change connections in the motor circuit, handling the load

current. More commonly they are arranged to make or break contacts in the auxiliary circuits of the controller to govern the action of the controller and cause it to stop the motor.

Ordinarily, limit switches merely cause the motor circuit to be interrupted so that the motor will stop. In some cases they cause a dynamic braking circuit to be made, quickly bringing the motor and machine to rest. In some cases they are arranged not to stop the motor but to automatically change the control circuits or conditions to bring about a change in speed. Limit switches are described further in Chap. XIV.

Overspeed Trip.—In some cases it is possible for a motor to drive a machine at a speed exceeding the safe or the desired rate. In such cases a speed-limit switch is sometimes used, this comprising some type of flyball device arranged to cause a circuit to be made or broken. These switches ordinarily handle only auxiliary circuits.

Interlocks.—A controller may comprise a number of units. These units must be so manipulated as to produce the desired connections and electrical conditions. There are many combinations possible which are not desirable and which will cause short circuits or other improper conditions. In order to eliminate the possibilities for improper operation of the various units which make up a complete control it is the practice to provide interlocks. These interlocks may take the form of mechanical connections, such as levers, preventing units from possible operation out of sequence. They may also take the form of auxiliary electrical contacts which serve to open certain circuits when other circuits are closed.

Interlocks may be provided between the units of a single controller as in the case of a control for a wound-rotor induction motor where an interlock may prevent closing the primary circuit when the secondary resistance is cut out. Interlocks may also be installed to tie together separate controllers governing motors handling related functions. For instance, an arrangement may be made to stop the motor handling the feed to a given machine if the process motor itself is stopped.

Field Discharge Resistors.—The function of the field discharge resistor is to protect the field windings against excessive voltages which may be induced in them when the field

circuit is opened. This voltage is caused by self-induction due to the rapid falling off of the field flux. Discharge resistors should be provided for all shunt- or compound-wound motors whose shunt field circuit will be opened. If the field circuit is permanently closed through the armature, a discharge resistor is not necessary. Discharge resistors should also be provided to protect the fields of synchronous motors whose field circuit may be opened. A field discharge resistor is so connected that, when the field is disconnected from the line, it is immediately short-circuited by the discharge resistor. The energy stored in the magnetic fields is then dissipated in the discharge resistor and the voltage induced is greatly restricted by the current thus produced.

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CHAPTER XIII

DIRECT-CURRENT MANUAL CONTROL

Starters and Controllers.—Electric motor control equipment may be considered as falling in two general classes, namely, motor starters and motor controllers. A starter, as its name implies, is arranged merely for starting and accelerating a motor to its running condition at intervals. A controller may be arranged for starting, stopping, reversing or other manipulation and is ordinarily under the frequent direction of an operator.

Direct and Remote Control.—Both starters and controllers may be further considered as of two types, namely, direct and remote. In the direct or manual type the device handled by the operator carries and controls the main motor circuits. In the remote type the operator handles only a push button or master switch carrying pilot circuits. The main motor circuits are handled by a device remote from the operator. Some remote starters or controllers are built to be operated pneumatically by means of switches closed by air-operated mechanisms. Much more commonly the remote controllers are operated by means of electro-magnets or solenoids. These controllers are commonly called magnetic controllers.

Types of Manual Starters and Controllers.—There is such a wide variety of commercial starters and controllers that all cannot be described. General types will be discussed and typical devices illustrated. Direct-current manual starters and controllers are constructed in multiple-switch designs, face-plate designs and drum designs.

Multiple-switch Starter.—The multiple-switch starter comprises a number of switches, closed by the operator in sequence to cut out the accelerating resistor in a number of steps. The last switch short-circuits the accelerating resistor entirely. The switches are specially designed with laminated leaf con-

tacts so that, when released by their holding-in device, they will all fall by gravity to the open position. They are ordinarily held in the closed position by a catch which is, in turn, held by a small magnet. This magnet introduces the no-voltage protection feature. Upon failure of voltage the magnet is de-energized, dropping the catch and returning the switches to "off" position. The switches are provided with mechanical interlock feature so that they cannot be closed except in proper sequence. The multiple-switch starter is a very good type,

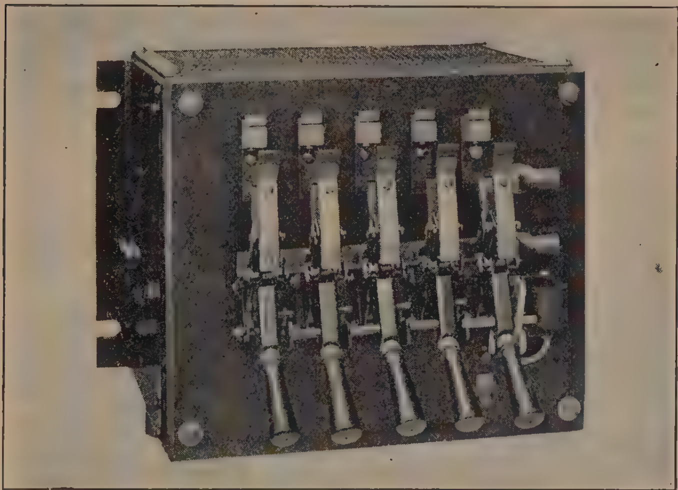


FIG. 127.—Multiple-switch starter for direct-current motor.

especially for the larger size motors. A considerable time period is required in closing the switches, giving a degree of protection against too rapid acceleration. The presence of a number of switches in parallel tends to prevent heating of the contacts, particularly that of the last switch. Upon opening, the switches break quickly any arc which might tend to form. Auxiliary contacts are provided to protect the laminated contacts from this arcing. Figure 127 illustrates a multiple-switch starter for a 40 hp. motor. Figure 128 gives the diagram of connections for this starter.

Face-plate Starters.—Face-plate starters predominate in the small motor field, primarily because of their simplicity and cheapness. The ordinary starter of this type comprises a lever carrying contacts which slide over and make contact with flat segments attached to an insulating plate. Figure 129 illustrates this type of starter as supplied for different size motors. Figure 130 illustrates a similar starter having its contact parts enclosed. The lever is held in running position by a retaining magnet. Upon failure of voltage this magnet releases the lever

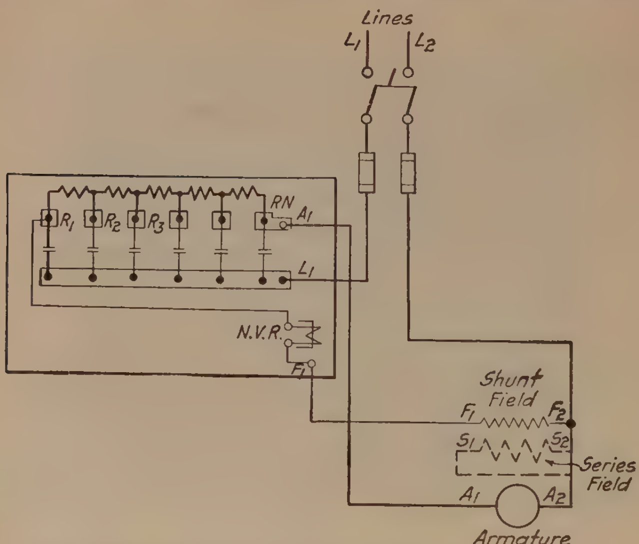


FIG. 128.—Diagram of connections of multiple-switch starter.

which is returned to "off" position by a spring. On all except the smaller starters laminated auxiliary contacts are supplied to shunt the face-plate contacts at the running position to prevent overheating. A device is also supplied to introduce a quick break of the arc resulting when the starter is returned to "off" position with power on or the arc resulting from discharge of the shunt-field inductive energy. Figure 131 is a diagram of connections for a face-plate starter for a 10 hp. motor.

Face-plate starters are frequently used where speed control by armature resistance is required. Arrangement is then made

so that the starting lever may be left on any intermediate position. In an ordinary starter the lever will return to "off" posi-

FIG. 129.—Face-plate starters for direct-current motors of various sizes.

FIG. 130.—Enclosed face-plate starter for direct-current motor.

tion unless held by the operator at an intermediate point or turned to full running point so that the retaining magnet may function. In the armature regulator a notched segment is used,

this segment being held by the no-voltage release magnet. This segment acts to retain the lever at any notch at which it is set. Upon failure of voltage the starting lever is released, returning to "off" position by action of a spring. Figure 132 illustrates an armature control starter or regulator for a 5 hp. motor. The resistor is self-contained and much more bulky than that supplied with the ordinary starter. The ordinary starter is limited to approximately 15 seconds starting duty at

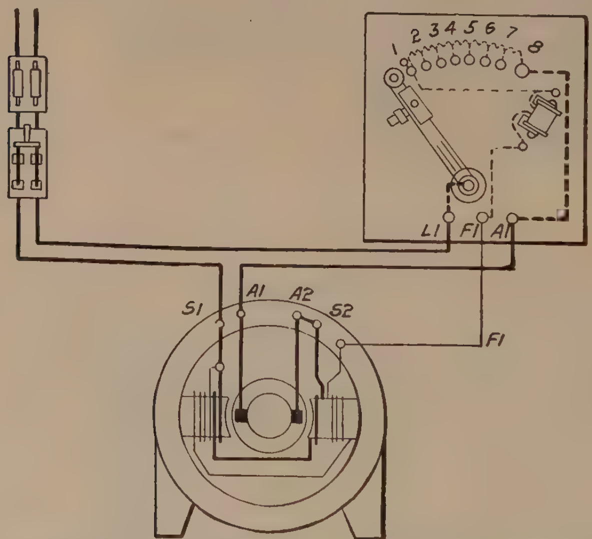


FIG. 131.—Diagram of connections of a face-plate starter for direct-current motor.

infrequent intervals. The resistors of the armature regulator must pass motor-load current continuously. This type of starter finds its greatest application, perhaps, in connection with fan drives for heating and ventilating systems.

Adjustable speed direct-current motors require both a starting device and a means for adjusting the strength of the shunt field. Face-plate starters are available, which include the necessary field rheostat for speed adjustment. These starters are so constructed that the motor is first accelerated to normal speed with full field. The no-voltage magnet then

FIG. 132.—Face-plate type armature resistance regulator for direct-current motor.

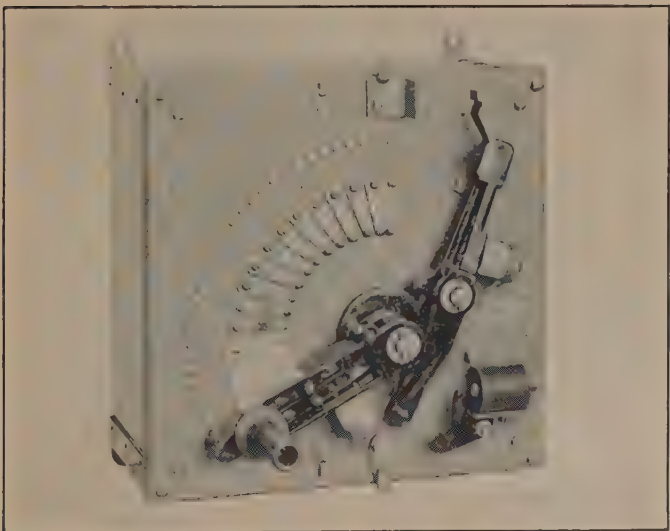


FIG. 133.—Face-plate type starter and field rheostat for direct-current motor.

retains the starting arm while the field control arm is moved across the field rheostat element, speeding up the motor. Upon failure of voltage, both arms return to "off" position. Figure 133 illustrates a starting and field-adjusting rheostat for a 10 hp. motor and Fig. 134 gives the diagram of connections for this starter.

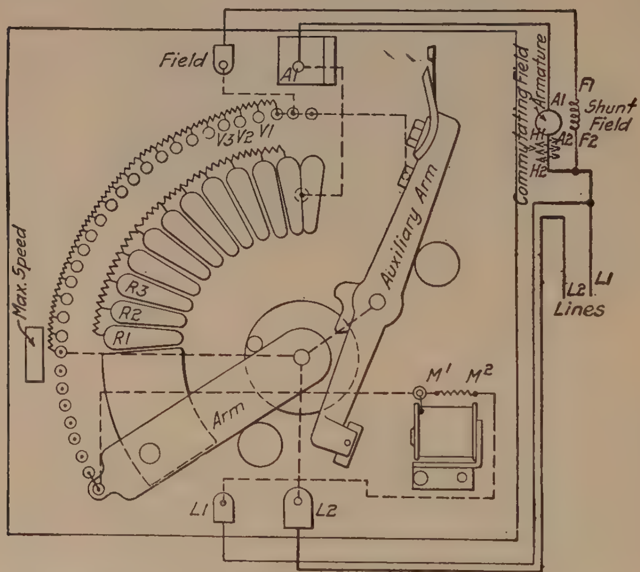


FIG. 134. Diagram of connections for face-plate starter and field rheostat for direct-current motor.

Face-plate Controllers.—The face-plate design is not restricted to the field of small motor starters. A number of more pretentious controllers are built on this principle. These controllers vary considerably in layout and design, according to purpose. They are more rugged in construction than simple starters as they are subjected to more continuous manipulation. They are generally laid out for reversing operation, being provided with two or more sets of segments so connected as to reverse armature or field connections. Magnetic blow-out coils are provided to help extinguish arcing at the contacts as the circuits are opened in stopping or reversing. The resistors

are usually contained in a frame integral with the controller. Figure 135 illustrates a simple reversing controller of this type. Figure 136 gives the diagram of connections for this controller.

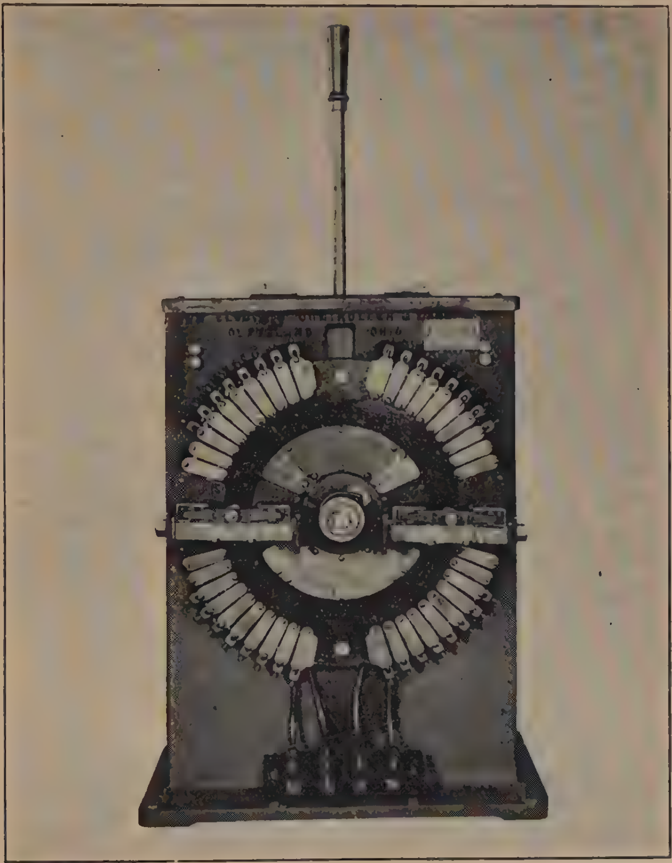


FIG. 135.—Face-plate type controller for direct-current motor.

Controllers of this type are used most commonly with series or heavily compounded motors, since these motors are best suited to manipulating drives. The advantages of the face-plate controller are simplicity, ruggedness, ease of operation, ease of speed control. The disadvantages are lack of protection

to motor due to pure manual control of acceleration, lack of flexibility in layout, severity of arcing, exposure of live parts, large space occupied and lack of protective devices.

Drum Controllers.—A drum controller comprises essentially a cylinder upon the surface of which are exposed a number

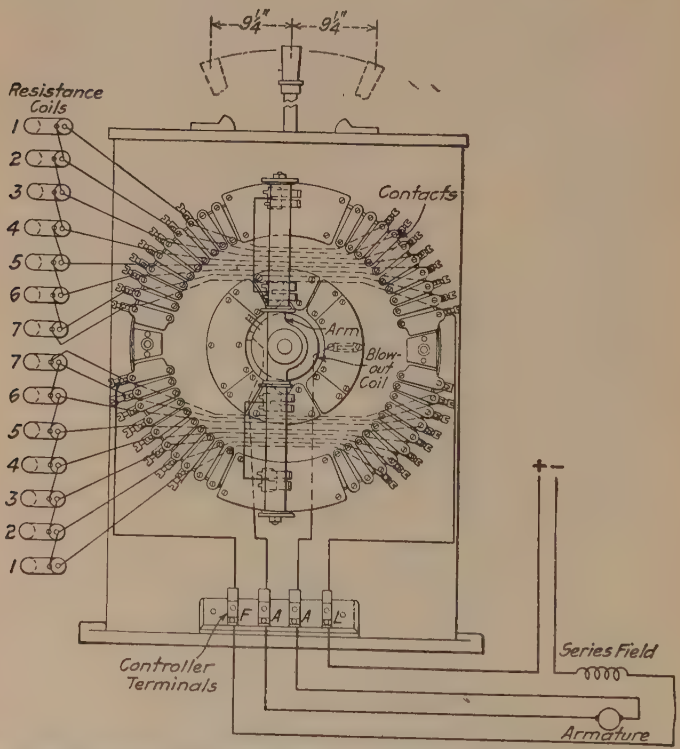


FIG. 136.—Diagram of connections for face-plate type reversing controller for direct-current series motor.

of conducting segments which may be connected to or insulated from one another, as desired. One or more series of flexible contact fingers, generally insulated from each other, are arranged to contact with the segments as the cylinder is revolved. By proportioning the arc covered by the respective segments and their angular position about the cylinder, the contacts can be made of desired duration and in a desired sequence.

The drum controller is a flexible design and is capable of many ramifications. The two most common designs are probably simple reversing controllers and hoist controllers. In the simple reversing controller contacts are supplied which serve to reverse either armature or field leads, as the drum is moved

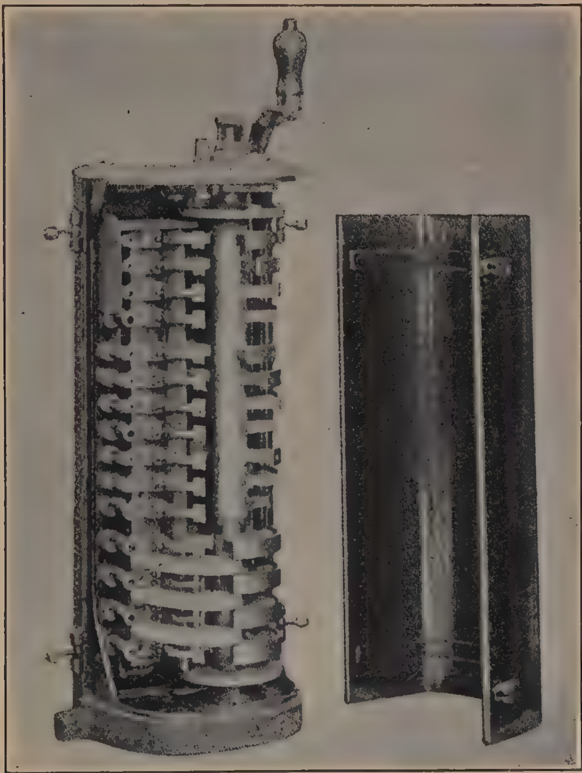


FIG. 137.—Drum type controller for direct-current motor.

to "forward" or "reverse" position. Other contacts cause the accelerating resistor to be cut out in a series of steps. With this type of controller operation is the same for both directions of rotation. Two distinct sets of segments are employed, one for forward, the other for reverse operation. Ordinarily, a single set of fingers contacts with the two sets of segments selectively according to the direction of throw of the cylinder or drum. A

drum controller has a number of positions corresponding to steps or changes in connections at the segments. These positions are distinguished by providing a "star wheel" and roller lever actuated by a spring. The roller drops into the grooves of the star wheel as the drum is revolved, distinguishing the various steps and preventing operation with the drum located at intermediate points, where contact would be uncertain. Figure 137 illustrates a drum controller for a 25 hp. motor. Figure 138 shows the connections for a simple reversing controller used in connection with a compound-wound motor. The segments are shown in a developed view. The controller is shown in the "off" position; the dotted lines show the position of the finger contacts for the various other positions of the controller.

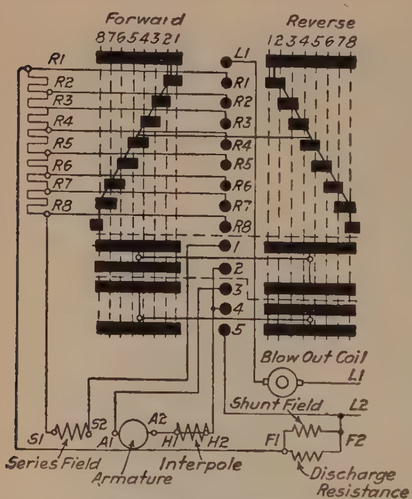


FIG. 138.—Diagram of connections for a simple reversing direct-current drum controller.

In order to prevent severe arcing when the circuits are interrupted, drum controllers are commonly equipped with magnetic blowout coils, which set up a magnetic field causing the arc to be extended and thus extinguished just as if "blown" by a blast of air. The blowout coils are commonly connected in the main circuits of the controller and are inactive when the drum is in the "off" position after the current is fully interrupted. In addition to the blowout coils, arc shields are supplied between segments to isolate the arcing and prevent short circuits due to this cause. The enclosing covers are removable to give access for inspection, maintenance and renewal of fingers and segments. The resistors are usually mounted separately, a number of connecting leads being required between drum and resistors.

The crane-hoist controller is a type in which a different sequence of connections is made for forward and reverse positions

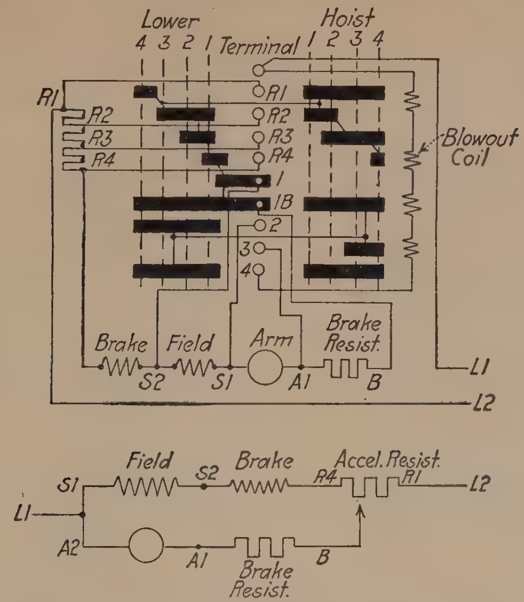


FIG. 139.—Diagram of connections for a drum controller for crane-hoist duty.

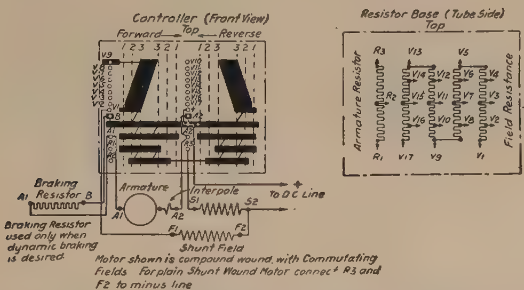


FIG. 140.—Diagram of connections for a drum controller for adjustable speed machine-tool motor.

of the drum. The forward or "hoist" position is arranged similarly to an ordinary reversing controller, simple acceleration and speed control by armature resistance being employed.

In the reverse or " lower " position an armature shunting principle is employed, the series field being connected across the line in series with resistance. On the first point the armature is shunted by the very low resistance of the series field giving a slow lowering speed but providing a positive downward drive of the hook. As the drum is rotated to subsequent positions

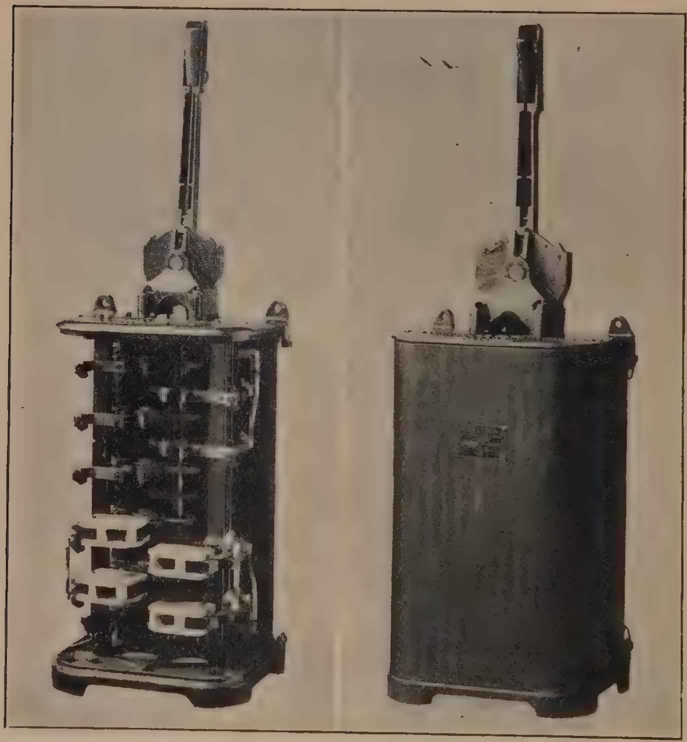
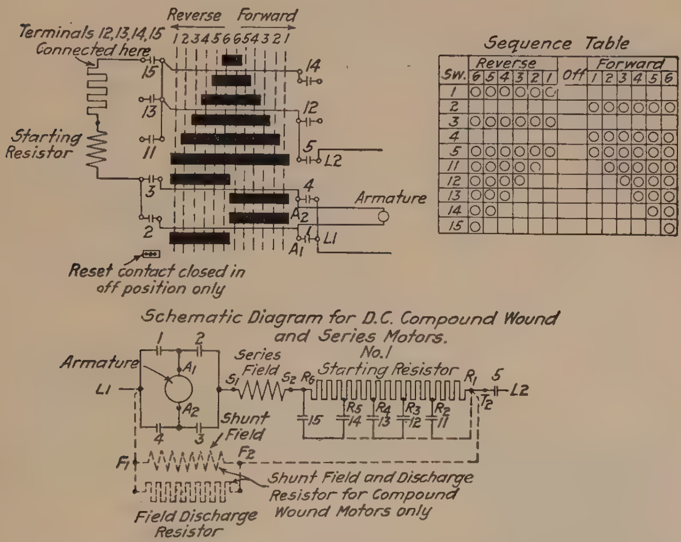


Fig. 141.—Cam type drum controller.

the resistance of the armature-shunt circuit is increased. This causes the armature voltage to increase so that the armature speeds up. The current in the motor armature may be either motor current, driving the light hook downwards, or generator current caused by the loaded hook tending to drive the motor downward, raising the counter-volts above the impressed volts and thus reversing the armature current. Figure

139 gives the diagram of connections for a simple drum-type crane-hoist controller. This is worked out to show the conditions existing when lowering.

The drum controller has been developed for the control of machine tool motors. It is quite extensively applied in this field. For constant speed motors the drum includes only armature reversing and accelerating points. If the motor controlled is of the adjustable speed type, a field rheostat feature is



Sw.	Reverse 6	5	4	3	2	1	Off	Forward 1	2	3	4	5	6
1	O	O	O	O	O	O							
2								O	O	O	O	O	O
3	O	O	O	O	O	O							
4								O	O	O	O	O	O
5	O	O	O	O	O	O		O	O	O	O	O	O
11	O	O	O	O	O				O	O	O	O	O
12	O	O	O	O						O	O	O	O
13	O	O	O								O	O	O
14	O	O										O	O
15	O												O

Fig. 142.—Diagram of connections of a cam type drum controller.

included, usually by means of a face-plate housed within the drum and operated by the same handle. Figure 140 shows the connections for a drum control of an adjustable speed machine-tool motor.

Drum designs are used, not only for direct-manual controllers but also, in the smaller sizes, for master switches to handle the pilot circuits of magnetic controllers. These will be considered more fully in later discussion.

Cam Type Drum Controller.—A considerable disadvantage of the ordinary drum controller rests in the fact that the contact fingers must slide on the drum segments, producing wear

and introducing arcing if the segments become roughened. More serious, perhaps, is the fact that the contacts are broken slowly and the separation between finger and segment is not great, so that it is difficult to avoid some arcing resulting in rapid deterioration of contact parts. In order to overcome these faults inherent in the drum design, a controller has been produced, similar to the drum controller in appearance but quite different in mechanism. In this controller a number of contactor units are provided, these units being held normally open by springs. The drum shaft is provided with a series of cams, each cam working in conjunction with a lever on one contactor unit. The cams are so profiled and so located angularly as to actuate the levers to produce the desired action of the individual contactor units. It may be seen that this design offers the flexibility of arrangement of the drum controller together with quick-breaking contacts and easily renewed contact parts. Figure 141 shows the make-up of a cam type drum controller while Fig. 142 is a diagram of connections for a standard reversing drum controller of this type.

Controllers of the drum type are sometimes arranged to be driven by a small motor which, in turn, may be governed either manually or automatically from some remote point. By this means a prescribed sequence of events can be provided, the time element depending upon the rate at which the motor rotates the drum. The drum may control the main motor circuits directly or it may serve as a master to govern the operation of a magnetic control.

Fig. 143. — Starter with graphite column resistor element.

Carbon Resistor Starter.—A distinctive type of starting rheostat is illustrated in Figs. 143 and 144. In this equipment the resistor comprises a column of graphite discs retained within a steel tube which is lined with a refractory insulating material. The lever is arranged to vary the compression upon the column of graphite discs.

This varies the contact resistance between discs and thus the total resistance of the column. At the full "on" position the resistor column is short-circuited by contacts on a face-

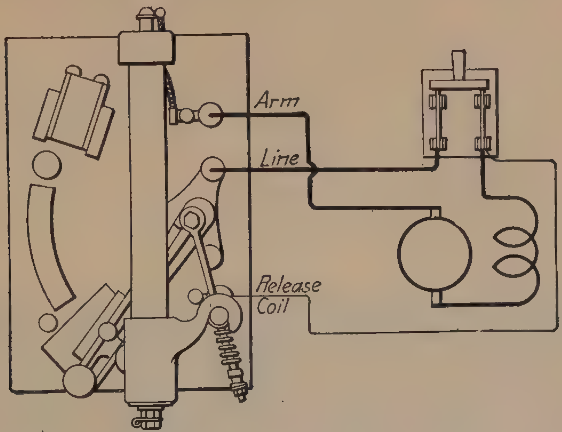


FIG. 144.—Diagram of connections for starter with graphite column resistor.

plate segment. This type of starter is compact and rugged. Its resistance element is free from troubles due to moisture or corrosion. A smooth acceleration without distinct steps is afforded.

CHAPTER XIV

DIRECT-CURRENT MAGNETIC CONTROL ELEMENTS

The need for starters and controllers which might be located remote from the operator and which might have automatic features, led to the development of many varied designs. The

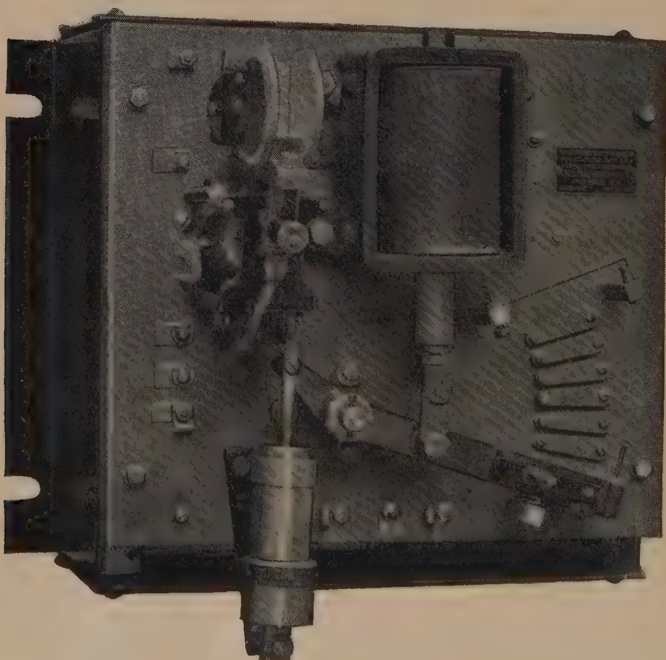


FIG. 145.—Solenoid operated face-plate starter for direct-current motor.

two types which have survived to greatest prominence are the solenoid starter and the unit contactor type of controller.

Solenoid Starters.—The solenoid starter is little more than a face-plate starter operated by a solenoid, with a dash pot

provided to delay the action to introduce the desired time element. Figure 145 illustrates a starter of this type and Fig.

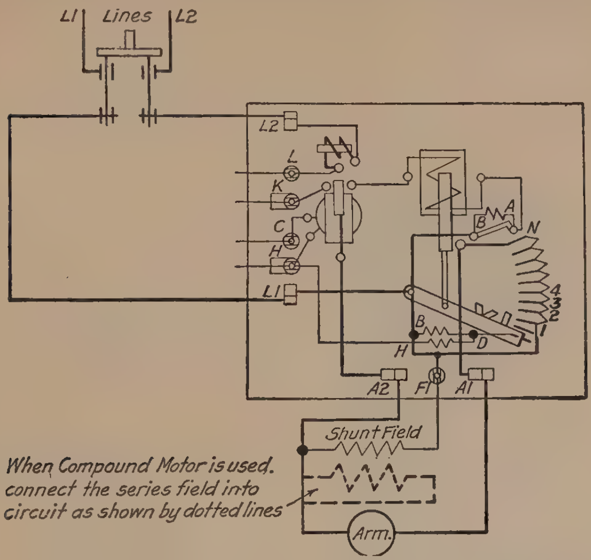


FIG. 146.—Connections for solenoid operated face-plate starter.

146 gives a typical diagram of connections. This type of device is restricted to starters for comparatively small motors. In this field it finds moderate use.

A solenoid type of starter employing a column of graphite discs as the resistor element, is also available. An equipment of this type is shown in Fig. 147 and the connections in Fig. 148. The solenoid which is used to exert the compressive force on the resistor column is provided with shunt and series windings, differentially connected. The shunt winding causes compression. The series winding opposes the action of the shunt winding and restricts the compressive force to

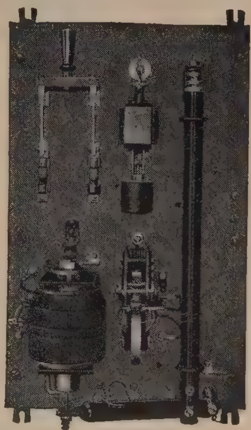


FIG. 147.—Solenoid operated starter with graphite column resistor.

a value which will just permit a given current flow. As the motor accelerates and the current tends to decrease, the series coil decreases its opposition and permits greater compression and a decrease of resistance.

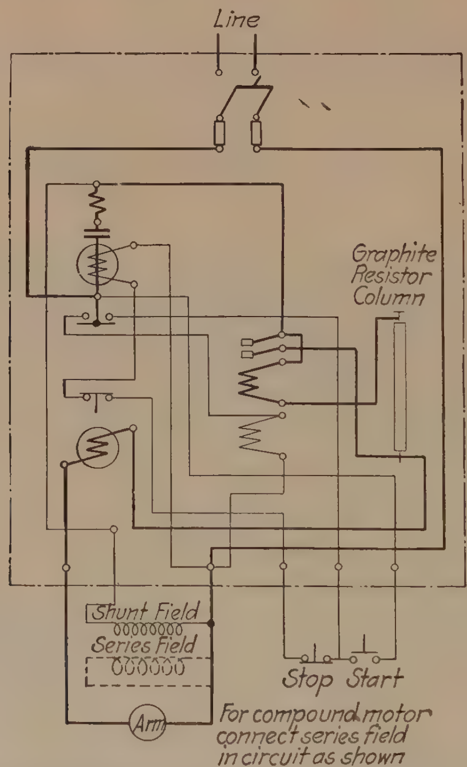


FIG. 148.—Connections for solenoid operated starter with graphite column resistor.

Contactor Type Controllers.—Unit type magnetic contactor starters and controllers are now used for the great majority of remote or automatic control applications. This type of control has a flexibility enabling its ready adaptation to a great variety of conditions. The performance can be most readily predetermined and adjusted. The control may be made to function independently of the operator, preventing motor

abuse. It is very convenient and relieves the operator of responsibility. These features, coupled with the satisfactory and reliable performance of the modern magnetic contactor, place this type in the front rank of motor control devices.

The unit type magnetic controller comprises an assembly of magnet-operated contactors each of which performs a function by opening or closing a circuit or circuits in such a manner as to contribute to the required performance of the controller as a whole. For instance, in a simple starter, one contactor may connect the motor to the line and other contactors may cut out the starting resistor.

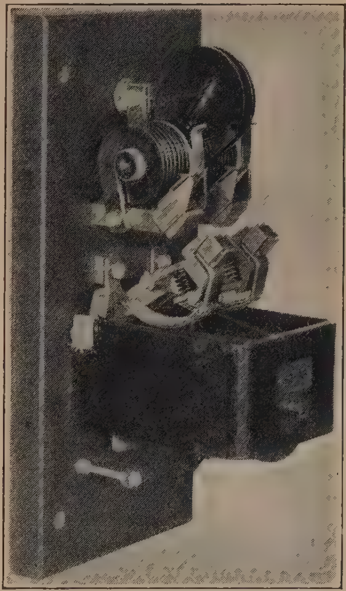


Fig. 149.—Clapper type direct-current magnetic contactor.

The Magnetic Contactor.—The basis of unit type magnetic control is the magnetic contactor. There are many designs of contactcrs, differing in details but similar in essential features. The so-called "clapper" type of contactor has been found by experience to be best suited for handling main circuits while the solenoid and plunger design is used extensively for relavs handling control circuits.

Clapper Type Contactors.—A clapper type magnetic contactor is illustrated in Fig. 149. It comprises essentially an iron yoke carrying a coil, an armature pivoted at its lower end and contact fingers attached to both stationary and moving elements. The contact fingers are ordinarily of solid copper. The design is such that these fingers make and break the circuit at their extreme tips but maintain the circuit through a line contact at the heel of the contact fingers. Figure 150 shows the different positions of a pair of contact fingers while closing.

The rolling effect is secured by mounting the movable contact on a hinged part, as shown. The spring functions to cause the tips to close first and open last. It also serves to permit the armature to close completely without rebound, exerting comparatively heavy pressure between the contacts. It also aids in causing the contactor to open with a quick, snappy action.

Although the contact fingers, when fully closed, have only a line contact, surprisingly heavy currents may be carried without undue heating. This is because a heavy pressure

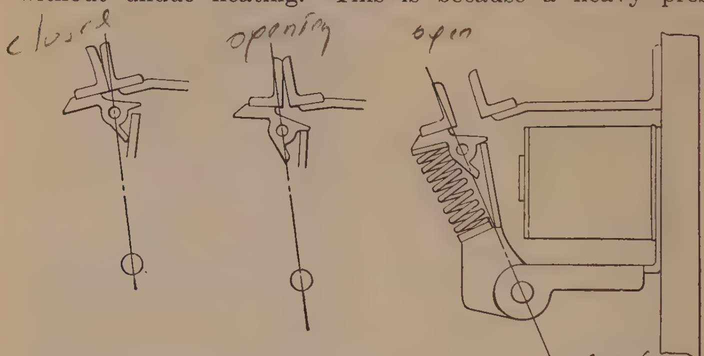


FIG. 150.—Positions of magnetic contactor fingers in ~~closing~~ opening, showing combined rolling and sliding action.

is exerted along the line of contact and also because the heat generated at the contact line travels quickly into the body of the contact fingers which are heavy enough to absorb and dissipate this heat. A magnetic blowout feature is provided on such contactors as are called upon to open circuits carrying heavy currents. There are many fine points in the design of contactors which have been developed through experience and which contribute to the successful performance of these units.

Most contactors function to close a circuit. When the coil is energized, the separated contact fingers are brought together. When the coil is de-energized the contacts are separated and the circuit is opened. The contactor opens by gravity assisted by the contact finger spring. Some contactors function to open a circuit which is normally closed when the coil is

de-energized. The spring-closed contactor shown in Fig. 151 is an example of this type. A contactor may be both circuit-opening and circuit-closing. Figure 152 shows a contactor of this type. The upper coil causes the upper contacts to close. When the coil is de-energized the contactor falls open by

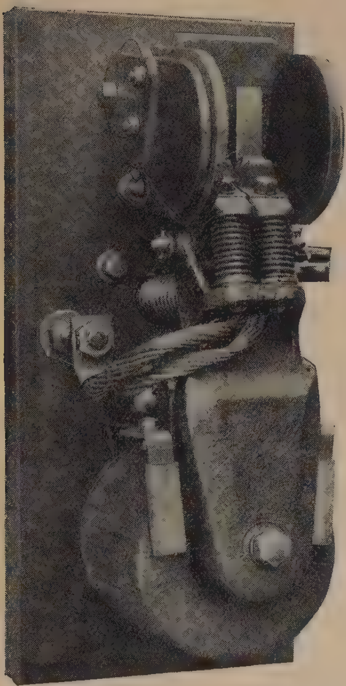


FIG. 151. — Spring-closed, magnetically opened contactor for direct current.

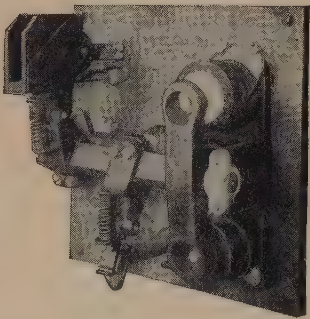


FIG. 152.—Direct-current contactor with gravity closed "back contact."

FIG. 153.—Two-pole direct-current contactor unit.

gravity, closing the lower contacts. The lower coil then acts to seal these contacts together under pressure and prevent a rebound. The majority of contactors are single-pole. Double-pole and multi-pole contactors find considerable use. Figure 153 illustrates a two-pole contactor.

Shunt Contactors.—The coil for a magnetic contactor is more commonly provided with a large number of turns of small

wire and is adapted to be connected across line voltage. A contactor of this type is called a "shunt" contactor. There are many variations. Some contactor coils are designed for less than line voltage and are connected in series with resistors. In some cases the coil is connected across full voltage while closing and a resistor is then cut in series with the coil by an auxiliary contact on the contactor. This is to give a brisk closing action and to reduce heating of the coil while merely retaining the armature in the closed position. Sometimes the coils of two or three contactors are connected in series across the line. Sometimes the coils are connected across the motor armature, responding to armature counter-volts. In other cases the coils are connected across the starting resistor, their action depending upon the resistance drop. These methods are all employed by different manufacturers and for different purposes.

Shunt contactors are commonly designed to close at a voltage somewhat less than their rated voltage so as not to be unduly affected by low-voltage conditions. These contactors, once closed, may be retained in the closed position on a relatively low voltage.

It will be appreciated that shunt contactors are operated by comparatively light currents which can be handled successfully by push buttons, master switches, relays, interlocks and similar devices in their control circuits.

Series Contactors.—The coil for a magnetic contactor may be made up of a few turns of heavy wire and adapted to be connected in series in the main motor circuit. The use of this construction is largely restricted to the so-called "series lockout" contactor. This contactor is designed for use with its coil in series with a circuit carrying a fluctuating current. The contactor is designed to "lock out" or hold open on high values of current but to close when the current falls to a prescribed value. This selective action is secured automatically through characteristics inherent in the contactor and not by means of auxiliary apparatus. This peculiar action is secured by providing the contactor with two magnetic circuits. The flux in one circuit tends to close the contactor. The flux in the other circuit has a net tendency to hold the contactor open. For high values of

current a considerable flux flows through the second or holding-out circuit due to the fact that the parallel portion of the first circuit is magnetically saturated. For lower values of current there is comparatively little flux through the holding-out circuit because the main circuit is not saturated and the air gap in the holding-out circuit introduces relatively high reluctance in that circuit. By adjusting this air gap it is possible to vary the current value at which the contactor will close. Figures 154, 155 and 156 illustrate the principal features of two different types of series lockout contactors both of which operate upon similar principles.

FIG. 154.—Series lockout contactor.

If the current through the coil of a series type contactor falls below the holding-in value, the contactor will drop open. Series contactors are made to hold in on relatively small currents, however. Sometimes a comparatively light shunt coil is provided to act as a holding-in coil after the series coil has closed the contactor. It may be noted that contactors with series coils may be de-energized either by opening the series circuit or by short-circuiting the operating coil.

Another type of series lockout contactor operates on a quite different principle. Figures 157, 158 and 159 illustrate a contactor of this type. Both the upper coil, tending to close the contactor, and the lower coil, tending to hold open the contactor, are series-wound. The iron in the circuit of the closing coil is worked near saturation. This coil exerts a strong pull at low current values with little increase after saturation is reached. The iron in the circuit of the lockout coil is not saturated, so that the pull of this magnet increases more rapidly with the heavy currents. For light currents the closing coil predominates and closes the contactor. For heavy currents the effect of the lockout coil is sufficient to hold

the contactor open. By changing an air gap in the magnetic circuit of the lockout coil the closing current value can be adjusted.

Auxiliary Contacts.—Contactors are frequently provided with auxiliary contacts of comparatively light construction. These auxiliary contacts serve to open or close pilot circuits to interlock or interrelate the functions of the individual contactor units.

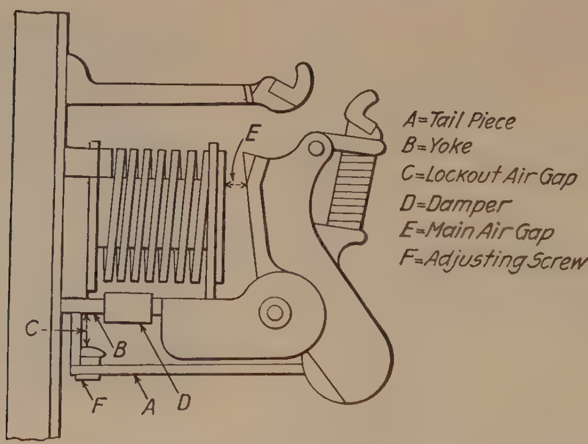


Fig. 155.—Diagram of the series lockout contactor shown in Fig. 154.

Relays.—Relays play an important part in the action of many magnetic controllers. The functions which they perform are varied. The designs are equally varied. They are commonly of either the clapper type or the solenoid and plunger type. They may carry shunt coils, series coils or both. A simple clapper type relay is shown in Fig. 160. This may be provided with a shunt winding, arranged to be connected across line voltage and used to provide a no-voltage protection feature. Upon failure of voltage the relay opens. It is so connected in the control circuit that it is then necessary to operate the push button or master to reset the relay and actuate the controller proper. Or the relay coil may be connected in series with the shunt field

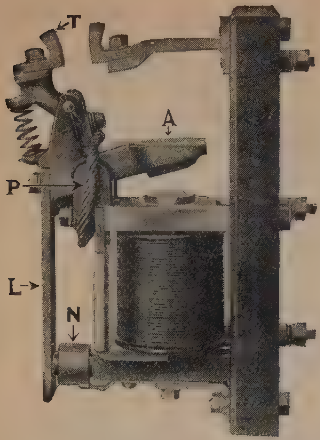


FIG. 156.—Another type of lockout contactor: *A*, armature; *T*, moving contact; *P*, pivot; *L*, tail piece; *N*, lockout adjustment.

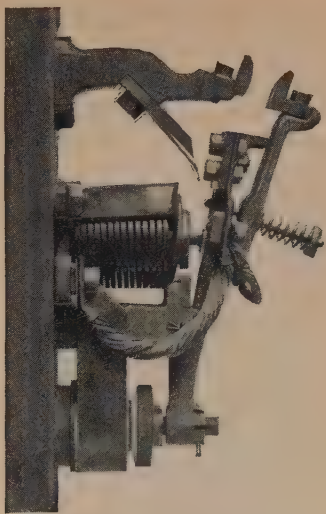


FIG. 157.—Series lockout contactor, two coil, opposed magnet type.

of a motor and the contacts arranged to open the main control circuit if the shunt field circuit opens. There are many uses for relays of this general type.

Time Element Accelerating Relay.—Accelerating relays are much used. Figure 161 shows an accelerating relay operating on a time element principle. When the relay coil (ordinarily shunt-wound) is energized, the armature closes instantly. This compresses a spring transmitting torque to the contact-bearing member, causing it to close slowly, retarded by the dash pot. This type of relay is used to control the cutting out of the starting resistor in motor acceleration.

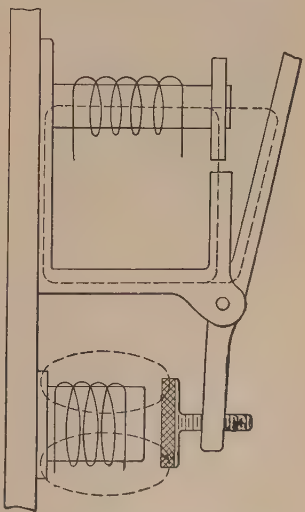


FIG. 158.—Schematic diagram of contactor shown in Fig. 157.

Current Limit Accelerating Relay.—Many accelerating relays operate on the current limit principle. They carry series coils and operate to hold open their contacts under heavy currents but to allow them to close when the current falls to a prescribed value. Figure 162 shows an accelerating relay of this type. Relays of this type are often mechanically inter-

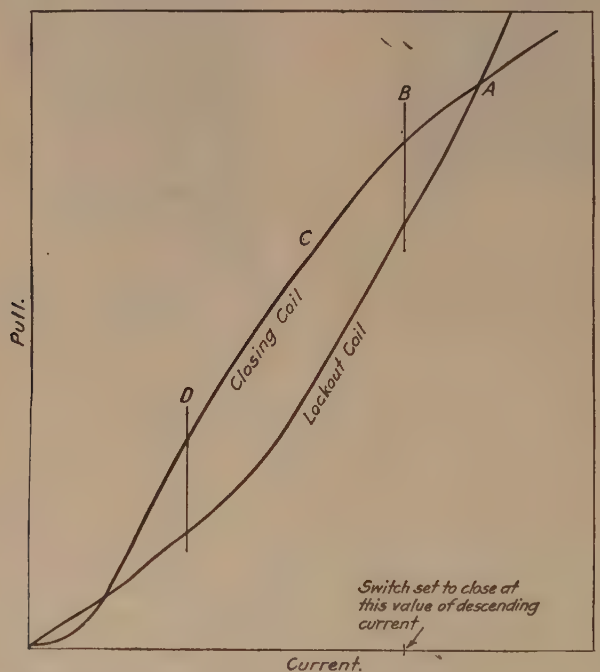


FIG. 159.—Magnetic conditions in series lockout contactor, two coil opposed magnet type.

locked with contactors so that they are held open mechanically until the contactor closes, allowing the relay to function to govern the further action of the controller. Other types of accelerating relays are described in connection with the controllers with which they are used. Refer to Chapter XV, pages 326 and 330.

Overload Relays.—Overload relays are provided on the great majority of control panels. They are also used in connection

FIG. 160.—Clapper type direct-current relay.

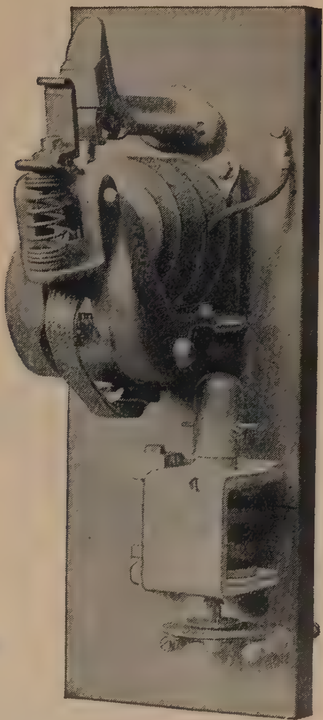


FIG. 162.— Accelerating contactor with current limit accelerating relay in conjunction.

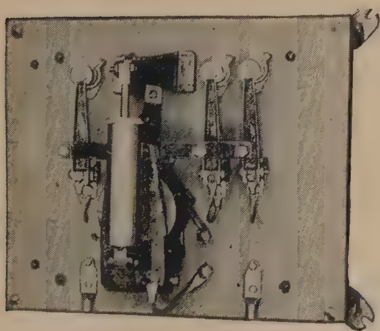


FIG. 161.—Time element accelerating relay.

with circuit breakers and contactors on protective panels. These relays are classed as instantaneous or time element types and may have instantaneous, automatic or hand reset provision. Overload relays are discussed more in detail in Chap. XII, pages 258 and following.

Fluttering Relay.—Some relays, series-wound, are so designed as to close at a definite current value, to hold closed at all greater currents and to fall open when the current falls below this value. A relay of this type is called a fluttering relay.

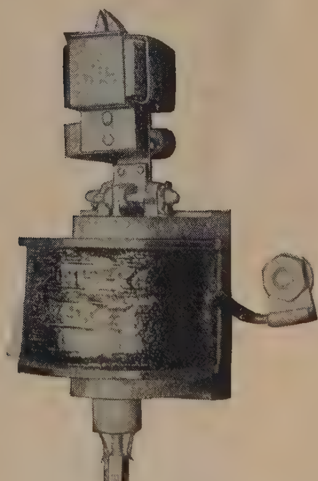


FIG. 163.—Fluttering relay.

FIG. 164.—Two-point push-button master switch.

One design is shown in Fig. 163. Relays of this type are often found on starters for adjustable speed motors. The relay coil is connected in the armature circuit. The relay contacts short-circuit the field rheostat while the motor accelerates or at any time that an overload occurs.

Time Delay Relay.—It is sometimes desired to introduce a time delay at some point in the functioning of a controller. This is more commonly accomplished by providing a relay equipped with a dash pot which will delay the operation to the desired extent.

Latching Relay.—Among the less common relay types is a solenoid and plunger device operating a ratchet and known

as a ratcheting or latching relay. Many other special relay designs are devised to meet particular requirements.

Master Controller.—The majority of motors are expected to function subject to the will of an operator. The device which enables the operator to govern the action of a magnetic controller is designated as a master switch. The simplest form of master switch is the push button. A unit or station comprising one or more push buttons enables the operator to start, stop, inch or otherwise govern his starter or controller. Figure

FIG. 165.—Pancake type master switch.

FIG. 166.—Internal arrangement of pancake type two-point master switch.

164 illustrates a common form of two-button push providing start and stop features only. This unit makes momentary contact in starting when the start button is depressed and a momentary break is made while the stop button is depressed. In other types the push-button circuits are not momentary. A walking-beam device is then used to interrelate start and stop or other functions.

A simple form of master switch is illustrated in Fig. 165, and its internal arrangement shown in Fig. 166. This master is somewhat more complex than the push-button type. It provides two directions of throw, usually arranged to give reverse the rotation of the motor. Two steps are provided in each

direction of throw, more commonly arranged to obtain two speed points. A contact is made at the "off" position of the master, usually serving as a reset for the no-voltage protective feature. This so-called "pancake" master is a simple and rugged device and serves excellently where the control required is comparatively simple.

More elaborate master switches are required when the control by the operator is more complete or complex. These masters more commonly follow the drum design, being, in reality, small drum controllers handling control circuits only.

Combined Direct and Remote Control.—In some cases direct and indirect control are combined in such a manner that the main motor circuits are handled partly in the manual controller and partly by a magnetic contactor panel. The manual controller carries pilot circuits also and serves the double function of controller and master. Masters of this type are usually of a modified drum design.

Fig. 167.—Combined drum reversing switch and master controller for direct-current motor.

Starting Accessories.—Some automatic starters are put in operation simply by closing the line switch. In the great majority of cases push buttons or master controllers are used. Sometimes it is desirable for a motor to function automatically and independently of any operator or attendant, being governed by some feature in connection with the process or operation performed. A variety of devices are employed for this purpose. More common among these may be mentioned float switches, diaphragm and gauge type pressure switches and regulators, thermostats, time clocks and humidostats.

Limit Switches.—A limit switch is a device actuated mechanically by some motion of the driven mechanism, to make or break a contact or contacts and thus to bring about a change in the action of the motor. More commonly the limit switch acts to cause the motor to slow down or stop as it approaches the

end of a cycle or travel. Most limit switches handle pilot circuits only, such an arrangement being generally preferable. They are sometimes arranged to handle the full motor current, however.

Limit switches, being contacting devices, take a variety of forms, being similar, in some cases, to mechanically actuated controllers or masters. Figures 168, 169, 170 and 171 illustrate respectively: hatchway, cam, screw and face-plate types. Hatchway and track limit switches are actuated by some form of trip device. The other types are usually coupled or geared to the driven machine.

Fig. 168.—Hatchway type limit switch.

Resistors.—Resistors for heavy current duty are commonly of the cast-iron grid type. This material is cheap, it has high resistance which does not vary widely with temperature changes, it will withstand high temperatures without deterioration and it is not vulnerable to corrosion. Its principal fault is its brittle nature. It is therefore not well suited to small currents where a light section would be required. For this service alloy wires or ribbons are used. The tube resistor unit is the prevailing type. This comprises an insulating tube upon which the resistance wire is wound, the unit being then treated with a cement or enamel to protect the fine wires and prevent oxidation and corrosion.

Graphite resistor columns, governed by compression, are also used to some extent in controllers specially adapted to their use.

A resistor must be capable of dissipating the losses originating within it without reaching a damaging temperature. The radiating surface must therefore be ample and suitable ventilation provided. The heat-absorbing or storing ability may also be a factor where the duty is of intermittent char-

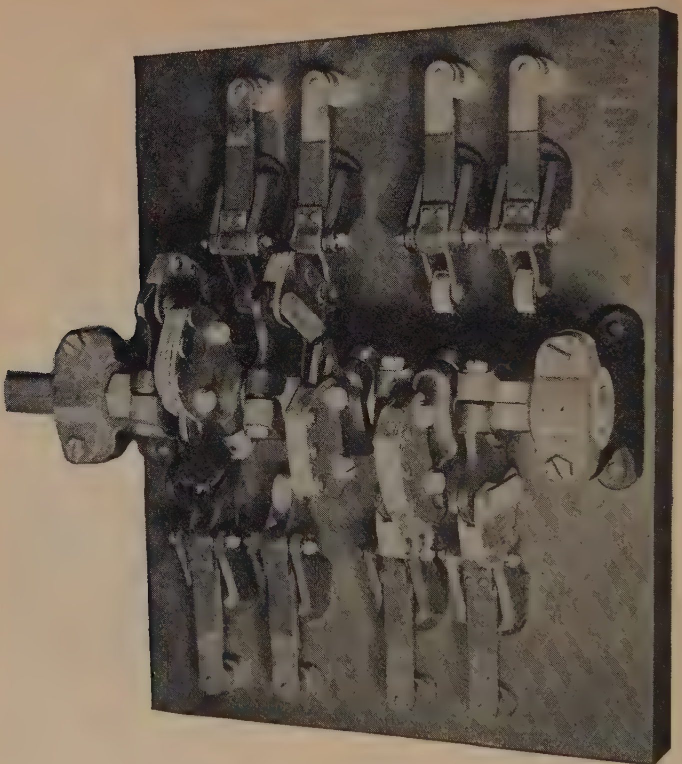


FIG. 169.—Cam type limit switch.

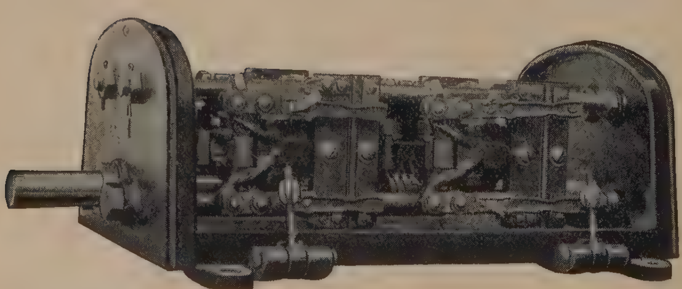


FIG. 170.—Screw or traveling nut type of limit switch.

acter as the heat generated in periods of service may thus be absorbed in part and dissipated during rest intervals. The

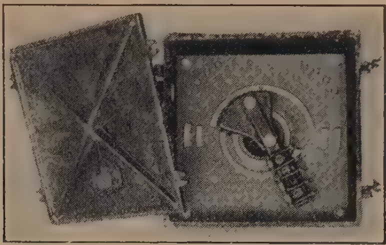


FIG. 171.—Face-plate type limit switch.

subject of resistors is treated at some length in Chaps. XI and XVI.

CHAPTER XV

DIRECT-CURRENT MAGNETIC CONTROLLERS

A magnetic controller comprises an assembly of unit contactors and relays so interrelated as to perform the required control functions. The requirements are extremely varied. As a result there are innumerable designs or assemblies differing in greater or lesser degrees. It would be impossible to describe, in limited space, any considerable number of control designs. We will therefore select for discussion a few of the simpler and more typical starters and controllers, representing the underlying principles as applied by different builders.

Automatic and Non-automatic Magnetic Controllers.—A magnetic controller may be either automatic or non-automatic. In a non-automatic controller each element responds to the master switch, all action being governed entirely by the operator. In an automatic controller the action is governed entirely or in part by means independent of the operator.

Automatic Control of Acceleration.—Automatic controllers and starters are built in great variety to accomplish a wide range of purposes. Nearly all of them include, in common, some means of automatically limiting to a safe value the rate of acceleration of the motor or motors they control. This may be accomplished in many ways. The methods may be broadly classified as follows:

Time element principle;
Current limit principle;
Counter-voltage principle.

Time Element Acceleration.—Time element starters cut out the accelerating resistors in a fixed time, regardless of the load. If the motor is so heavily loaded that it will not start on the first point, the series resistor is slowly cut out until the motor starts or the overload protective devices function. The timing

is usually adjusted to accelerate the motor properly under its worst load condition. Therefore the time taken is longer than necessary for light loads.

The two principal types of time element starters use dash pots or contactors operated by a pilot motor. The dash pot type is the more common. Both air and oil dash pots are used. The timing of the air dash pot is controlled by varying the amount of air admitted to the pot. As the opening is necessarily small, it is liable to clog with dust and change the timing. If the air dash pot is not oiled occasionally, the leather dries and destroys the action. Too much oil is also bad. The timing of air dash pots varies to some extent with the temperature. Oil dash pots are less liable to clogging than air dash pots. They sometimes tend to pump oil. The timing varies materially with temperature changes and the many special oils developed to overcome this difficulty are not entirely successful. The principal advantages of the time element principle are its simplicity and the definite assurance that the accelerating resistor will be cut out and the motor accelerated if at all possible. Because they will always start the motor, they are less subject to tampering than some other types.

Time element starters of the pilot motor type are in quite common use for the larger size motors. The pilot motor commonly actuates a drum cylinder or a cam shaft. This type of equipment is, in general, more expensive than the dash-pot type for small sizes but in the large sizes it may cost less. It is possible to get very long timing with this type and the timing is accurate and independent of disturbing conditions.

Current Limit Acceleration.—The two principal methods of current limit acceleration utilize series lockout contactors and series accelerating relays. Series lockout controllers are popular because of their simplicity. Practically no electrical interlocks are required and they are less liable to coil trouble due to the fact that series coils are used. They are quite easily adjusted. They must be adjusted for the worst possible condition. They are full-automatic and are not suited to applications where speed control is desired. They require series coils of different description for each size of motor. Sometimes, on light loads, the accelerating contactors will not hold closed.

They are not suited where overhauling loads are involved, as the contactors will drop open when the load passes through zero. Series lockout contactors were described in the previous chapter and the operation of some controllers of this type is discussed on following pages.

Series relay controllers are more complicated than any of the other standard types as a series relay and a shunt contactor are required for each point of acceleration. Electrical or mechanical interlocks are required. They are more flexible than series lockout controllers and are suited for use where speed control is desired as the accelerating contactors may be made to respond both to the series accelerating relays and to the master controller. Series relay controllers have been

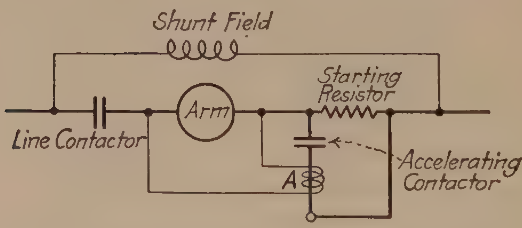


FIG. 172.—Principles of simple counter-voltage starter.

extensively used for the more complex requirements but the multi-point and voltage drop relay types, which also act on the current limit principle, are now being adopted in many instances for similar duty. Controllers of all these types are described in this chapter.

Counter-voltage Acceleration.—In the counter-voltage type of controller the acceleration is governed by the counter-voltage generated in the motor armature as it attains speed. The accelerating contactor coils are connected across the armature, as in Fig. 172, or across the armature and portions of the accelerating resistor, as in Fig. 173. The coils and air gaps are calibrated so that the contactors will close at the proper voltages. In the controller shown in Fig. 172 the voltage across coil *A* increases as the armature accelerates, until the current becomes sufficient to close the accelerating contactor and short-circuit the accelerating resistor. In the controller shown in Fig. 173

the contactor coils are connected into different points in the starting resistor. With this scheme no interlocks are required and it is not necessary to adjust the contactors for different

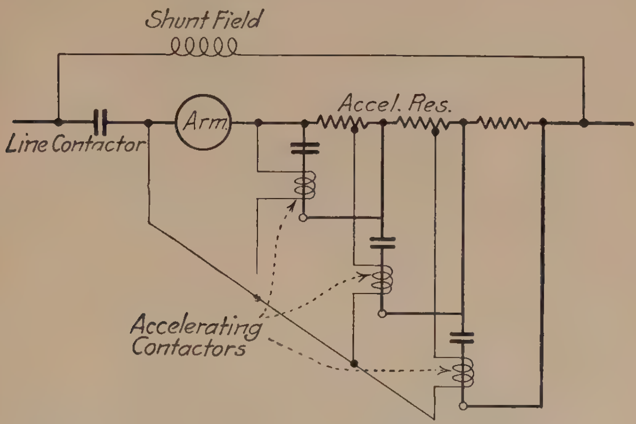


FIG. 173.—Principles of counter-voltage acceleration.

closing voltages because this is taken care of by the drop across the starting resistor.

Figure 174 shows a method of counter-voltage acceleration used by the Otis Elevator Company. Instead of using several

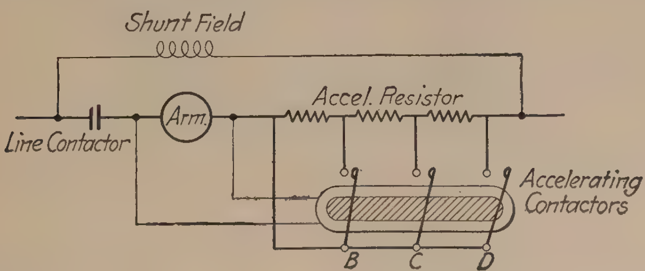


FIG. 174.—Counter-voltage starter with single magnet for accelerating contactors.

single-pole contactors, one large magnet is used, with several armatures *B*, *C*, *D*, the air gaps of which are adjusted so that the contacts will close in sequence at different voltages.

Counter-voltage starters are open to the objection that they do not operate properly on widely fluctuating loads. Moreover, their operation is affected by the heating of the contactor coils. When the controller is cold the contactors will close on a much lower voltage than when hot. The principal advantages of this type of controller are simplicity and freedom from interlocks.

TIME ELEMENT STARTER

Composition.—A simple magnetic starter, based upon time element acceleration, is shown in Fig. 175, and the connections given in Fig. 176.

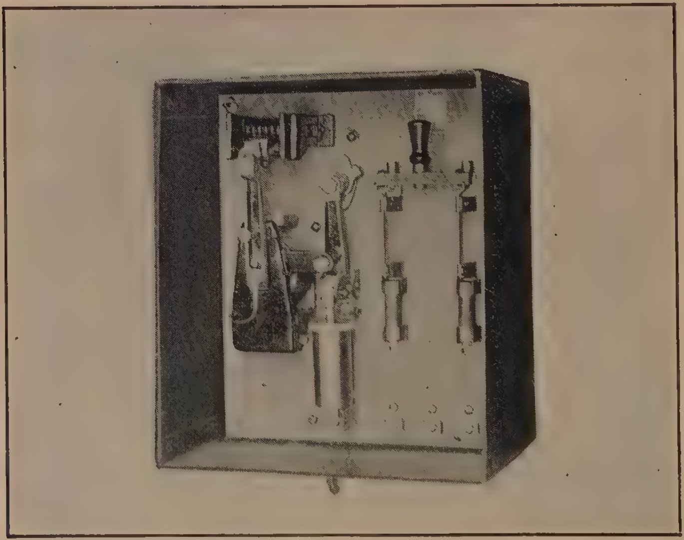


Fig. 175.—Simple time element starter for direct-current motor.

The units required for this starter are as follows: a knife switch to disconnect motor and control from the line; fuses for overload protection; a shunt-line contactor 1 to open or close the main motor circuit; a time element accelerating contactor to cut out the accelerating resistor. Control is by a two-point push button with " start " and " stop " functions.

Operation.—When the " start " button is depressed the line contactor closes, connecting the motor across the line in series with the accelerating resistor. Closure of the line contactor 1 depresses a spring tending to close contacts 11. The closure of the contacts is delayed by an oil dash pot, allowing the motor

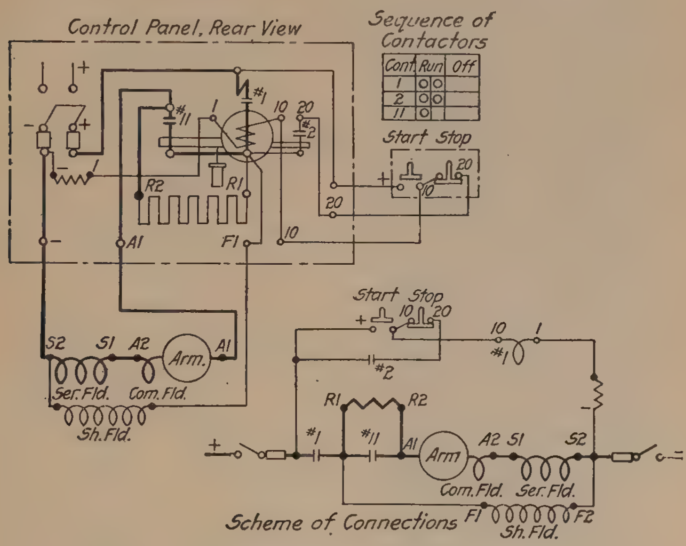


FIG. 176.—Connections for simple time element starter.

time to accelerate before the starting resistor is cut out. The " stop " button causes both 1 and 11 contacts to open by opening the circuit of the line contactor coil.

STARTER FOR ADJUSTABLE SPEED MOTOR

Composition.—A magnetic starter for an adjustable speed motor is shown in Fig. 177. The connections are given in Fig. 178. The contactor units which make up this starter are as follows: A knife switch is supplied to disconnect the motor and control circuits and to provide overload protection. A shunt line contactor 1 serves to open and close the motor circuit. Two accelerating contactors 11 and 12, operated on armature counter-voltage, serve to short-circuit the acceler-

ating resistor. Control is by a "start" and "stop" push button. The action of the starter may be described as follows:

Fig. 177.—Magnetic starter for adjustable speed motor.

Off Position.—The main motor circuit is open at contactor 1. Motor and control circuits have potential unless the line knife switch is opened.

Operation.—Push "start" button. This establishes a control circuit from positive source through knife switch and fuse, through line contactor coil 1, through the normally closed "stop" button, through the normally open "start" button, through fuse and knife switch to negative. This closes line contactor 1, which, in turn, closes its auxiliary contacts. The closing of these contacts establishes a holding circuit independent of the "start" push button, so that when this button is released, contactor 1 remains closed.

The closing of line contactor 1 completes the main circuit from positive source through the knife switch and fuse, through contactor 1, through the field relay series coil, through the starting resistor, through the motor armature and series fields

and through the switch to negative line. The motor now starts.

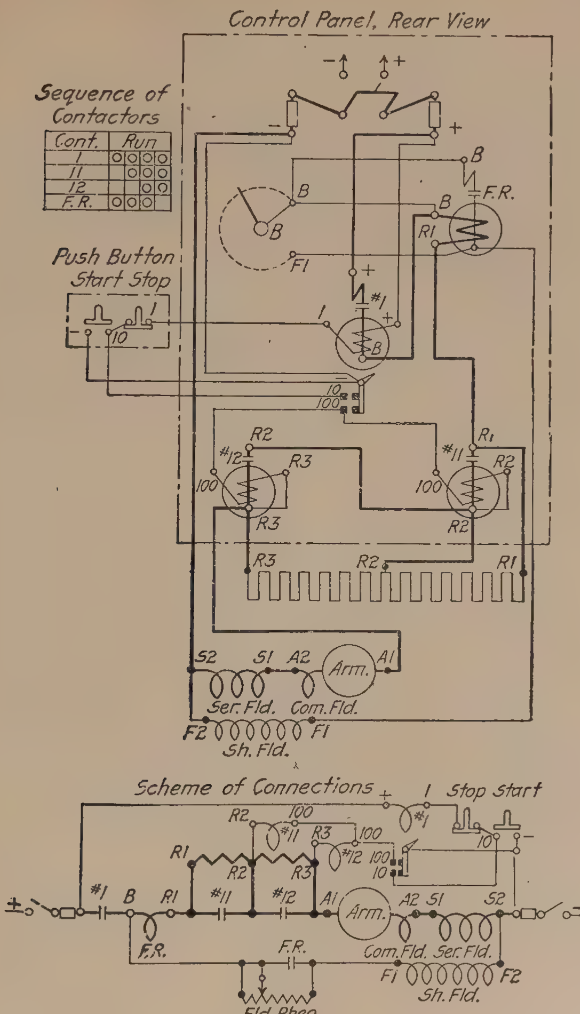


FIG. 178.—Connections for starter for adjustable speed motor.

Upon the first rush of current through the circuit, the field relay closes, shunting the field rheostat and providing full shunt-field current. As the accelerating current falls off the field

relay may open. This introduces the motor field rheostat resistance. Weakening the shunt field tends to speed up the motor. This increases the load and closes the field relay. This relay will likely flutter a few times while the motor is accelerating, after which it will remain definitely open unless a heavy load comes on the motor, when it will close and tend to slow down the motor, which, in most instances, will relieve the load.

The closing coil of accelerating contactor 11 is connected across the armature and a portion of the resistor. When the motor is first started there is little voltage across the armature, hence no tendency for this contactor to close. As the motor speeds up, the counter-voltage increases. When the counter-voltage has attained a value of perhaps 150 volts, the closing coil of 11 contactor is sufficiently energized to close that contactor and cut out the step R_1–R_2 of the accelerating resistor.

As the armature accelerates further the counter-voltage across the shunt closing coil of accelerating contactor 12 increases to a point where this contactor will close. This short-circuits the rest of the accelerating resistor. The motor now attains full speed corresponding to the field rheostat position. It will be noted that the coils of accelerating contactors 11 and 12 are now subject to full line voltage. They, therefore, close positively and remain closed.

Stop.—When the "stop" button is depressed the main pilot circuit is opened, causing line contactor 1 to open the main motor circuit.

Overload Protection.—Overload protection is provided through the use of fuses in the main circuit. There is no further protection against field failure.

No-voltage Protection.—Failure of line voltage causes contactor 1 to drop open, its closing coil being deenergized. It is then necessary to depress the "start" button to start the motor.

REVERSING CONTROLLER WITH SERIES ACCELERATING CONTACTORS

Composition.—A simple reversing controller with plugging and accelerating currents limited by series lockout contactors,

is illustrated in Fig. 179. The connections are shown in Fig. 180.

The units which comprise this controller are as follows. A

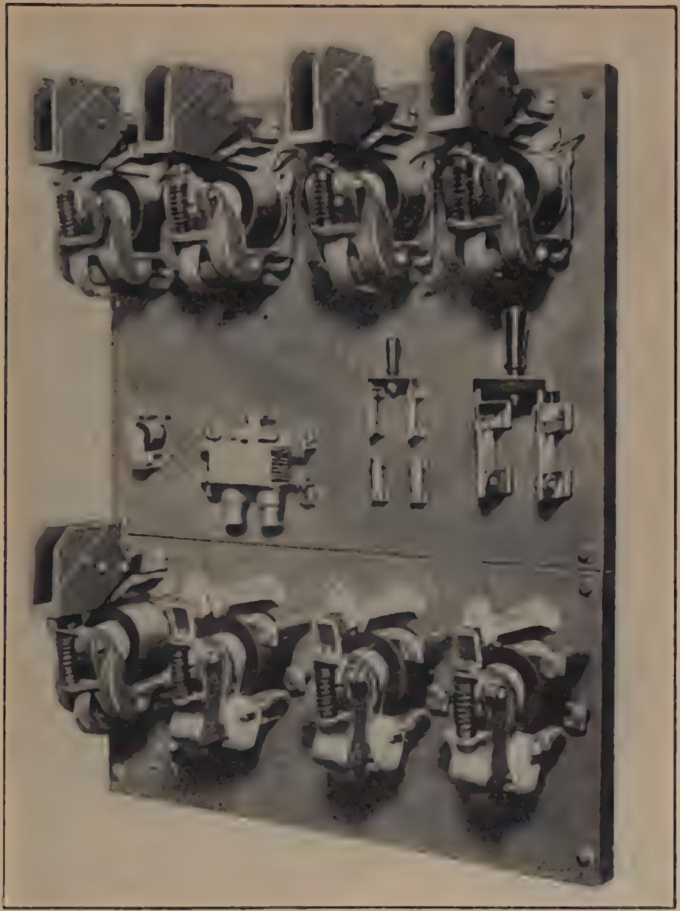


Fig. 179. Reversing controller with series accelerating contactors.

knife switch is supplied to disconnect the motor and main controller circuits from the line. With this arrangement it is possible to try out the controller with the main knife switch open and the motor at rest. Four shunt contactors 1, 2, 3,

4 are supplied to reverse the armature connections. A shunt line contactor 5 is supplied to disconnect the motor from the negative line. Three series lockout contactors 11, 12, 13 serve

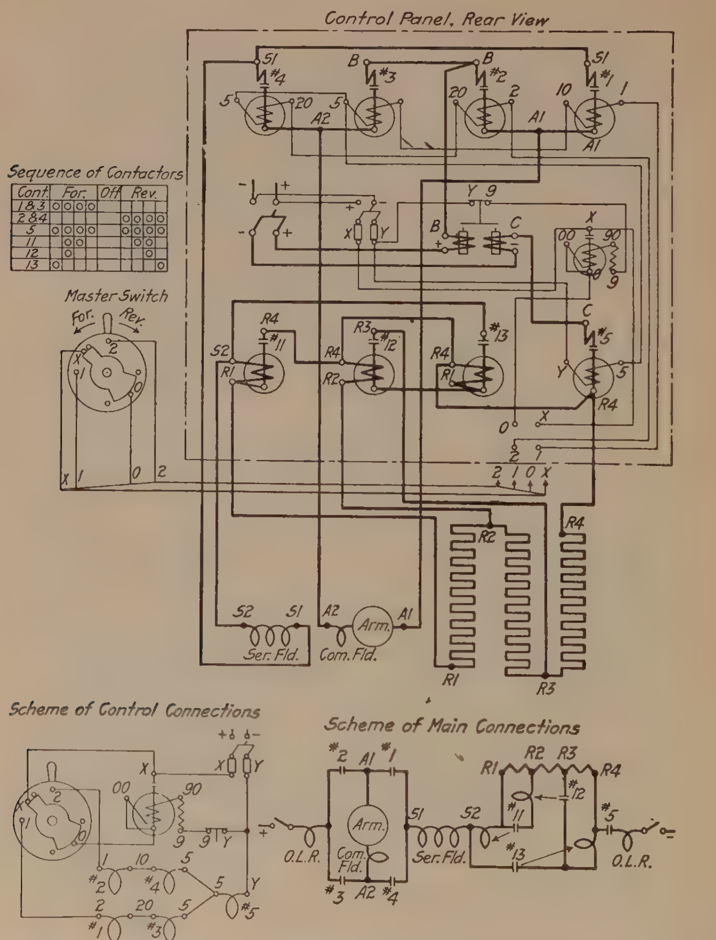


FIG. 180.—Connections for reversing controller with series accelerating contactors.

to cut out the accelerating resistor. A two-coil overload relay, instantaneous or time trip, instantaneous reset, is supplied for protection, the coils being connected in the main circuit

next to the positive and negative lines. The presence of this relay in conjunction with the line and directional contactors at the ends of the motor circuit, protects against a heavy flow of current into the motor from either line due to a ground. A voltage relay is supplied to afford no-voltage protection. Control is by a simple reversing master switch. The action of the controller may be outlined as follows:

Off Position.—The master establishes a circuit from positive line through coil of voltage relay to negative line, causing the voltage relay to close. A circuit is then established from positive line, through the voltage relay contact and coil and overload relay to negative line. This circuit does not include the master. The voltage relay therefore remains closed when the master leaves the off position. The voltage relay opens either upon failure of voltage or when the overload relay opens. It is then necessary to return the master to off position to reset the voltage relay. Until this is done the motor will not start as the main contactors cannot close unless the voltage relay is closed.

First Step Forward.—The master completes a connection from positive to shunt coils of directional contactors 1 and 3 and line contactor 5. This control circuit passes through the voltage relay contact, through master, thence through the shunt coils of contactors 1, 3, 5, in series, thence to negative. The main circuit is now closed from positive line, through overload relay coil, through directional contactors 1 and 3 and armature, through series field, through coil of series lockout contactor 11, through the entire accelerating resistor, through line contactor 5, through overload relay coil to negative.

Second Step Forward.—Master and all shunt coils remain as on first point. The current through the series lockout coil 11 drops to such a value as to permit accelerating contactor 11 to close, shunting out resistor R_1–R_2. The main circuit is now from positive through overload relay coil, armature and directional contactors, series field, through accelerating coil and contactor 11, through the series lockout coil 12, through a part of the resistor, namely R_2–R_4, through line contactor 5 and overload relay coil to negative line.

Third Step Forward.—This differs from the first and second

steps only in the amount of resistance in circuit. The current through series lockout coil 12 drops, allowing accelerating contactor 12 to close, shunting out resistor R_3–R_4, and leaving only resistor R_2–R_3 in circuit.

Fourth Step Forward.—The current in series lockout coil 13, now in circuit, drops, allowing contactor 13 to close. This shunts the entire resistor and the series lockout coils 11 and 12, allowing these contactors to open.

Reverse Direction.—Same as forward except that directional contactors 2 and 4 are operated, through point 2 on the master, instead of directional contactors 1 and 3, effecting reversal of current through the armature.

Plugging.—This control may be adapted for plugging service by use of sufficient resistance R_1–R_4, to limit the plugging current peaks. Series lockout contactor coils and settings should then be adjusted so that contactor 11 holds out for plugging but closes quickly when starting from rest. Resistor R_1–R_2 then serves as extra resistance to limit plugging peaks only. Resistor R_2–R_4 is normal starting resistance.

Overload Trip.—Excess current through either or both overload relay coils, due to a ground, or to overload on the motor, will break the control circuit at the overload relay, de-energizing the voltage relay coil, as described above.

General Comment.—It is to be noted that accelerating contactor 13 is held closed by the load current through its series closing coil. If the load falls to a low value or becomes overhauling, this contactor will open, reinserting the accelerating resistor. This may or may not be a serious objection.

It may be further noted that no speed control is possible where series accelerating contactors are used. The master merely starts and stops the motor. Acceleration is entirely automatic and independent of the operator.

REVERSING CONTROLLER WITH TIME ELEMENT ACCELERATION

Composition.—A simple reversing controller with speed control and with plugging and accelerating currents limited by a time element relay, is illustrated in Fig. 181, the connec-

tions being shown in Fig. 182. The units comprising this controller are: a two-pole knife switch to disconnect motor and control from the line; four shunt contactors 1, 2, 3, 4, interlocked mechanically, for reversing the armature connections; a circuit-breaker contactor 5, for disconnecting motor and control from the negative line; three shunt accelerating contactors 11, 12, 13, for cutting out starting and plugging resistors; a time element accelerating relay; a single-pole knife switch to

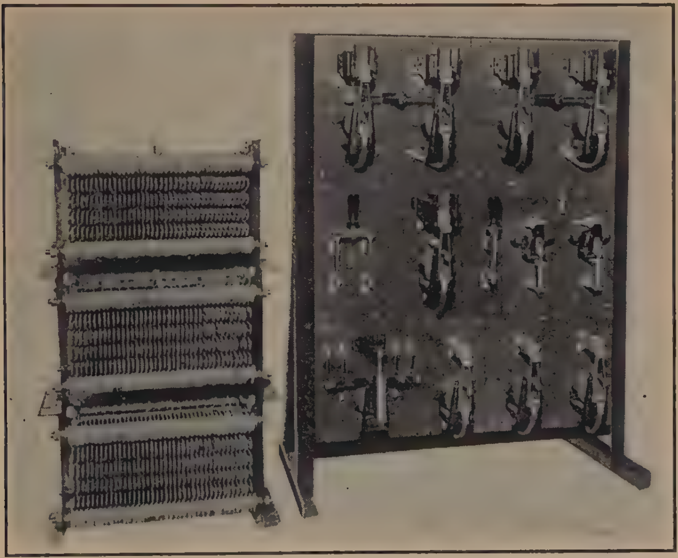


FIG. 181.—Reversing controller with time element acceleration.

permit testing the controller with the motor inoperative; two inverse time trip, instantaneous reset overload relays and a suitable master switch. The action of the controller may be outlined as follows:

Off Position.—The master switch completes a circuit through the closing coil of circuit-breaker contactor 5, causing this contactor to close. An auxiliary holding-in contact on 5 contactor then serves to retain this contactor closed when the master leaves the off position. If contactor 5 is opened during operation by action of the overload relays, it becomes neces-

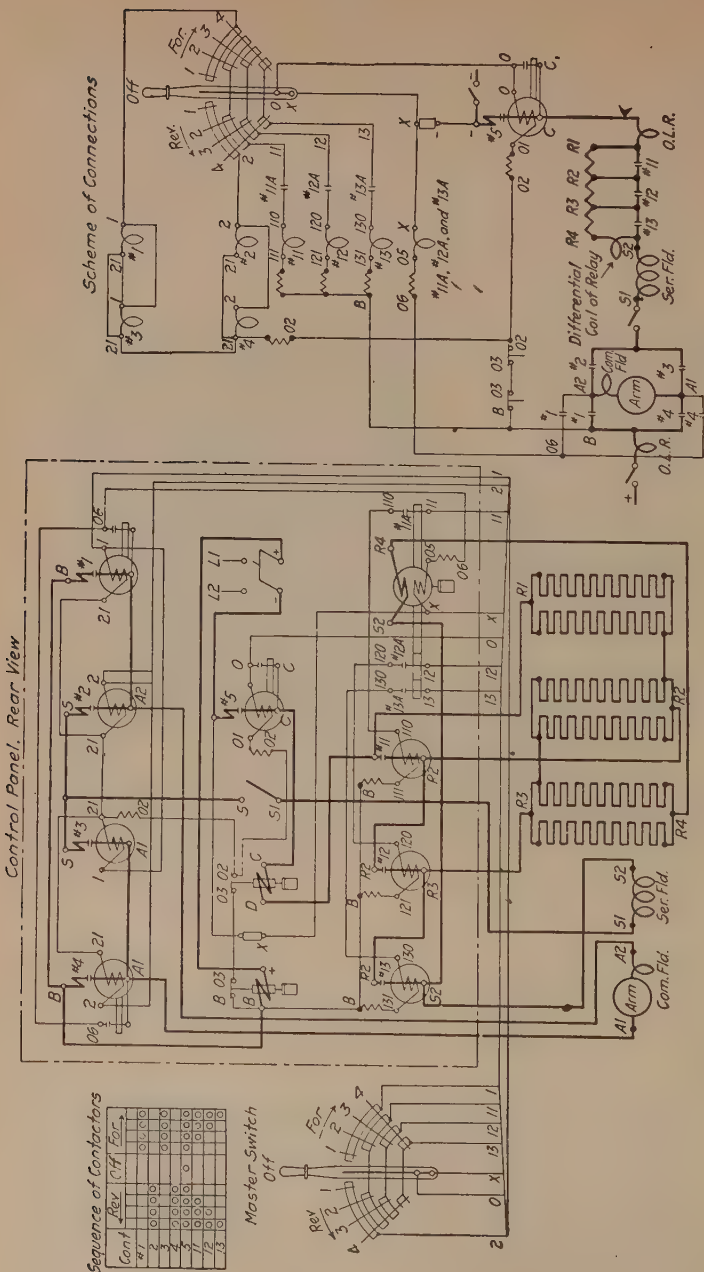


FIG. 182.—Connections for reversing controller with time element acceleration.

sary to return the master switch to off position to again close this contactor.

First Point Forward.—The master switch completes a circuit through the closing coils of directional contactors 1 and 3. This circuit passes through the overload relays so that the tripping of the overload relays will, in addition to opening the 5 contactor, also open the directional contactors. When the main circuit is closed through contactors 1 and 3, the motor starts.

When contactor 1 closes it also closes an auxiliary contact which completes a circuit through the shunt coil of the accelerating relay. This relay is also acted upon by its series coil which is included in the motor circuit and which opposes the action of the shunt coil. Unless the motor current is very heavy the relay will close, compressing a spring tending to close the relay contacts 11*a*, 12*a*, 13*a*. The closure of these contacts is delayed by an oil dash pot, allowing the motor time to accelerate before the starting resistor is cut out.

Second Point Forward.—The master switch completes a circuit through the closing coil of accelerating contactor 11 so that this contactor will close when accelerating relay contact 11*a* is closed. A portion of the accelerating resistor is short-circuited by contactor 11.

Third Point Forward.—The master switch completes a circuit through the closing coil of accelerating contactor 12, causing it to function similar to contactor 11, reducing the accelerating resistor.

Fourth Point Forward.—The master switch completes a circuit through the closing coil of accelerating contactor 13, causing it to function similar to contactors 11 and 12, cutting out all of the accelerating resistor.

Reverse Direction.—Same as forward except that directional contactors 2 and 4 close instead of contactors 1 and 3, effecting reversed flow of current through the armature.

Plugging.—This control may be adapted for plugging service by insertion of sufficient plugging resistor R_1–R_2 to act in conjunction with accelerating resistor R_2–R_4 to limit the current peak. The starting from rest may be slightly delayed with this arrangement. In this connection it may be noted

that the dash pot on the accelerating relay does not delay the opening of that relay. This obviates the danger of plugging with this relay partially closed, hence with the accelerating resistor partially cut out.

Overload Trip.—Excess current through either or both overload relays, due to a short, overload or ground, will open the circuit of circuit-breaker contactor 5 and the directional contactors, causing them to open. The auxiliary contacts on the directional contactors are thus opened, causing the accelerating relay to open.

No-voltage Protection.—In case of failure of voltage with the master in other than the off position, contactor 5 falls open. It is then necessary to return the master to off position to reset this contactor.

Acceleration and Speed Control.—If the master be thrown quickly to last point, the acceleration is governed by the time element of the dash pot modified by the action of the series coil in delaying the action of the shunt coil of the accelerating relay. Contacts 11*a*, 12*a*, 13*a* are arranged angularly so that they close in sequence at intervals. The relative intervals are subject to adjustment.

If the master be thrown to first point and later advanced to further points, the accelerating relay may have already closed so that the accelerating contactors are closed as rapidly as the master is advanced. Ordinarily this does not cause a high rush of current as the greatest peaks usually occur during the initial acceleration.

The control may be modified by causing the shunt closing coil of the accelerating relay to be energized on the second rather than the first point. Acceleration beyond the first point is then delayed, the relay functioning when the second point is reached.

REVERSING CONTROLLER WITH SERIES ACCELERATING RELAYS

Composition.—A reversing controller with acceleration limited by series relays and giving two points of speed control is illustrated in Fig. 183. A diagram of a similar controller is shown in Fig. 184.

FIG. 183.—Reversing controller with series accelerating relays.

The controller shown in the diagram comprises a main line switch and a fused control switch for disconnecting the motor and control circuits. Four shunt contactors 1, 2, 3, 4 are

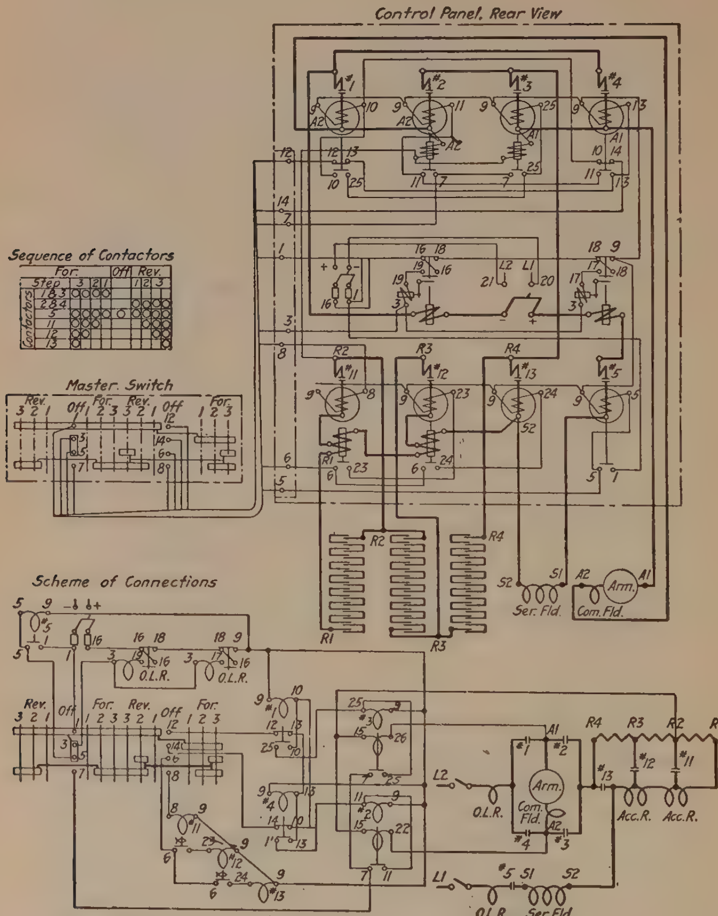


FIG. 184.—Connections for reversing controller with series accelerating relays.

directional contactors. These are mechanically interlocked. Shunt contactor 5 is a circuit-breaker switch. There are three shunt accelerating contactors 11, 12, 13. Two overload relays

are supplied. The master is of the drum type with two rows of fingers. The action is as follows:

Off Position.—A circuit is completed in the master switch, energizing the closing coil of contactor 5. When this contactor closes its auxiliary contact completes a holding-in circuit independent of the master.

The reset coils of the overload relays are also energized with the master in the off position.

First Point Forward.—The closing coil circuit for contactor 1 passes through an auxiliary contact of contactor 4. This auxiliary contact is closed when contactor 4 is open. In this manner an electrical interlock is provided for the directional contactors in addition to the mechanical interlocks. With the master on the first point forward the closing coil circuit for contactor 1 is completed. When this contactor closes it completes the circuit for the closing coil of contactor 3. The closure of these two contactors (5 remaining closed) starts the motor with full accelerating resistor in circuit.

Second Point Forward.—The shunt relay connected with contactor 3, is connected across the accelerating resistor R_3–R_4. In starting the motor from rest, the voltage drop across this resistor is insufficient to hold up this relay, so it drops. This completes a circuit from negative source through the auxiliary contacts of contactors 4, 1, 3 to the lower section of the drum. When the master moves to second point, a circuit is completed from the lower section of the drum through the closing coil of accelerating contactor 11. The closure of this contactor steps out some of the accelerating resistor.

Third Point Forward.—With the master on this point the circuit for the closing coil of contactor 12 is completed at the master and through the contacts of the series relay connected with contactor 11. So soon as the motor current falls sufficiently for this relay to drop contactor 12 will close.

The closing circuit for accelerating contactor 13 is taken from the same point on the master and passes through the contacts of the series relay connected with contactor 12. As soon as the motor current permits this relay to drop, contactor 13 closes, cutting out all of the accelerating resistor.

The purpose of the two-part series coils on the accelerating

relays is to give these relays an excess power to hold up the plunger except at the time the relay is to drop at its set value. At this time only a portion of the series coil is in circuit.

Reverse.—Operation in the reverse direction is identical except that directional contactors 4 and 2 close instead of 1 and 3, reversing the current flow through the armature.

Plugging.—The resistor is so designed that R_2–R_4 is sufficient to limit the current to a safe value in starting the motor from rest. Resistor R_1–R_2 is additional resistance to absorb the additional voltage in plugging due to the line voltage and counter-voltage being momentarily additive. To protect the motor on plugging, the shunt relays are provided in connection with contactors 2 and 3. These relays, shunted across the resistor R_2–R_4, do not have sufficient voltage impressed to remain open when the motor is started from rest. When the motor is plugged, however, the voltage impressed on these coils is higher so that the relays hold up until the plugging voltage falls off.

Overload Protection.—The two overload relays adjacent to the positive and negative lines, fully protect the motor. This type of relay is held closed by a catch. This catch is released by a plunger in case of overload. The relay then remains open by gravity until closed by the reset magnet which is energized only at the off position of the master. The overload relays open the control circuits for all contactors.

No-voltage Protection.—Upon failure of voltage, all contactors drop open. Circuit-breaker contactor 5 will then remain open until the master is returned to the off position.

Performance.—The curves in Fig. 185 set forth the speeds which will result with varied loads and with different amounts of accelerating resistor in circuit. The curves refer to a control arranged for plugging duty. When the motor is plugged the full resistor R_1–R_4 is in circuit. If the motor be plugged when running at 500 r.p.m. (negative speed) a current peak of about 230 amp. will result, as shown by the values for curve A. As the motor decelerates this current will fall off, following curve A. When the motor comes nearly to rest the closure of contactor 11 reduces the resistor in circuit to R_2–R_4. A momentary peak of about 200 amp. results as

indicated on curve *B*. If the master is held on second point the motor will now have a characteristic as shown by curve *B* and will assume a speed corresponding to its load as indicated by some point on curve *B*. If the master be moved to third

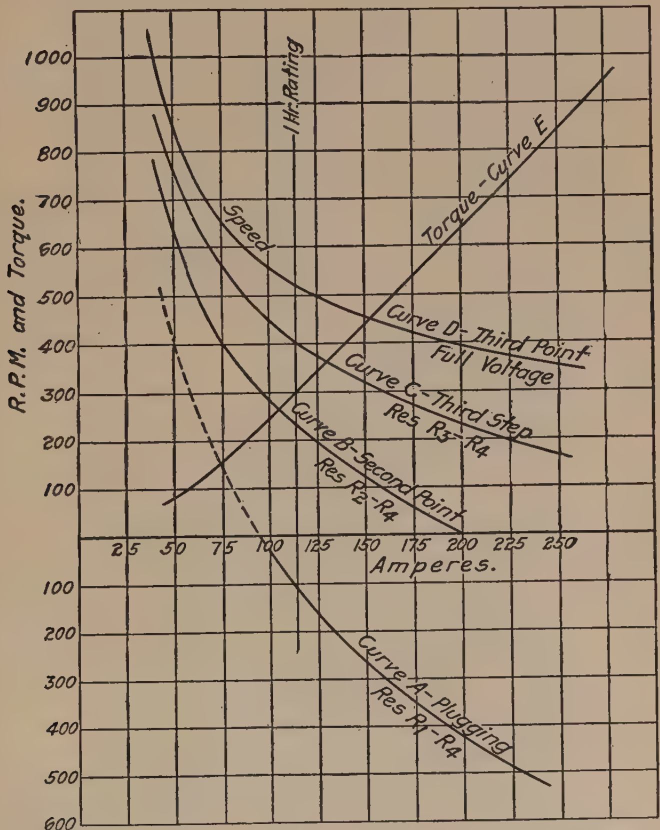


FIG. 185.—Characteristic curves of series motor with accelerating resistor in series.

point, the accelerating resistor will be reduced to R_3–R_4, by closure of contactor 12. If the motor happens to be rotating at 300 r.p.m. when contactor 12 closes (indicated on curve *B*) a current peak of about 160 amp. will be taken when the resistance is reduced. The motor will then accelerate to some such

point as indicated on curve C, when contactor 13 will close. A peak of about 190 amp. will now be taken, as indicated on curve D. The motor will continue to accelerate until it reaches a speed normal to its working load, as indicated by some point on curve D. For all positions, the torques corresponding to varied current values are shown by curve E.

REVERSING CONTROLLER WITH MULTI-POINT CURRENT LIMIT ACCELERATING RELAY

Composition.—A simple reversing controller with speed control and with plugging and accelerating currents limited by a single relay working on the current limit principle, is illustrated in Fig. 186. The connections are shown in Fig. 187. This equipment is similar to that using a plurality of series relays for current limit acceleration except that a single relay is here employed to perform the same functions as the several series relays.

The units comprising this controller are: a two-pole knife switch to disconnect motor and control from the line; a control circuit switch, four directional contactors 1, 2, 3, 4, interlocked mechanically; a circuit breaker contactor 5, three shunt-wound accelerating contactors 11, 12, 13; a multi-point accelerating relay; a voltage relay and a double-coil overload relay. The action of the controller may be outlined as follows:

Off Position.—The voltage relay remains closed, independently of the master, giving no-voltage release only. All other contactors are open.

First Point Forward.—The master completes a circuit through the closing coils of directional contactors 1 and 3 and circuit-breaker contactor 5. When these contactors close, the motor is connected across the line with full accelerating resistor R_1–R_4 in circuit.

Acceleration.—The accelerating resistor is cut out in steps by the accelerating contactors 11, 12 and 13. These contactors are governed by the accelerating relay the action of which will be briefly explained.

This relay is illustrated in Fig. 188. It comprises a magnet core having two coils. There are two sets of pivoted armatures.

On one side are the accelerating armatures D, E, F provided with contacts. On the opposite side is the release armature C.

FIG. 186.—Reversing controller with multi-point current limit accelerating relay.

The accelerating contacts are normally open, being held in this position by spring H. When the coil is magnetized the armature C closes, releasing the accelerating armatures D, E, F.

These armatures are retained by the magnet, however, against the pull of springs K. As the magnetism decreases, the armatures D, E, F release and close their respective contacts. By properly adjusting the air gap, these armatures may be made to release at different values of magnetism, as desired. Each armature closes a contact which energizes the coil of an accelerating contactor.

It was remarked that this relay magnet is provided with two coils. Coil A is so connected as to have impressed across it the voltage drop of the accelerating resistor. Coil B is

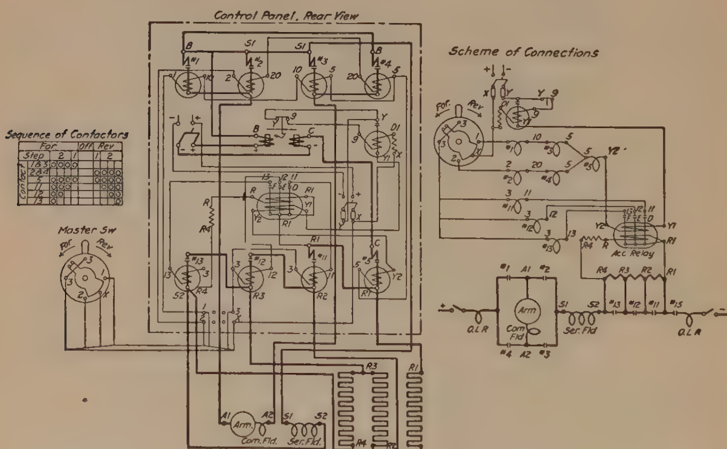


FIG. 187.—Connections for reversing controller with multi-point accelating relay.

arranged to be energized to a constant value whenever the main contactors are closed to start the motor. When the motor is first started the full line voltage is taken up in the resistor. Relay coils A and B are both energized. Armature C is attracted and armatures D, E, F retained. As the motor accelerates, its counter-voltage increases so that the resistance drop decreases. The voltage across relay coil A decreases, weakening the magnetism and allowing armature D to be released. This closes the control circuit for accelerating contactor 11, short-circuiting a section of accelerating resistor. The motor current now increases but, as the motor accelerates

further, its counter-voltage increases, again reducing the voltage across the accelerating resistor and across relay coil A, which is connected across this resistor. The magnetism in the relay core now falls off, permitting armature E to release. This closes contactor 12, which short-circuits another step of accelerating resistor. Further acceleration of the motor permits armature F to release, causing accelerating contactor

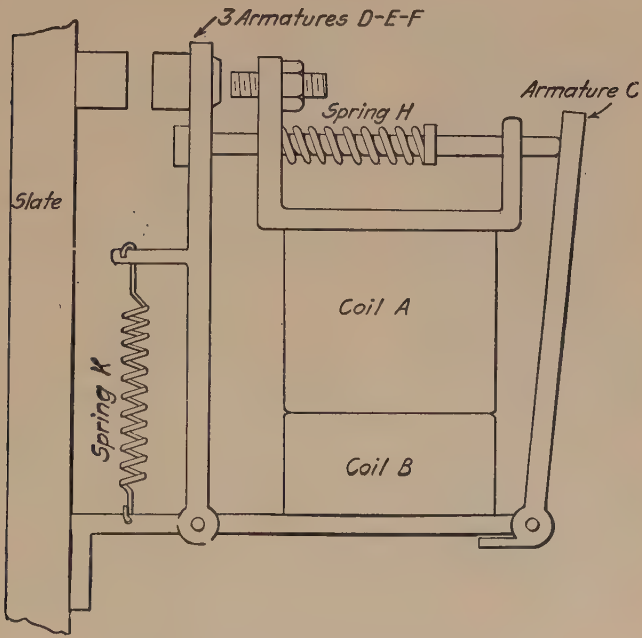


Fig. 188.—Multi-point accelerating relay.

13 to close, connecting the motor across the line. The voltage across coil A is now zero. Coil B remains energized, however, and furnishes sufficient magnetism to retain armature C in the closed position.

Reverse Direction.—Operation in both directions is the same except that for the reverse direction, contactors 2 and 4 close instead of contactors 1 and 3.

Plugging.—This control may be adapted for plugging service by insertion of sufficient plugging resistor R_1–R_2 to

act in conjunction with accelerating resistor R_2–R_4 to limit the current peak. The drop across the resistor R_1–R_4 will exceed line voltage when the motor is plugged. The relay must be adjusted accordingly.

Overload Protection.—Excess current through either or both overload relays will open circuit-breaker contactor 5 and the directional contactors which happen to be closed at the time. The overload relay shown is of the hand reset type and remains open when tripped.

Advantages.—The controller here shown is merely one example of a wide variety of controllers which may be based on the principle and use of the multi-point current limit accelerating relay. The principal advantages offered by this arrangement over the plurality of individual current limit accelerating relays, may be briefly enumerated.

A simpler and more compact controller results, having fewer parts, in less variety.

The amount of main circuit wiring and connections on the panel are reduced.

A multiplicity of different relay coils are required, according to motor rating, when series relays are employed. On the other hand, one accelerating relay of the type described is applicable to an entire range of motors of a given voltage.

Series relays are subject to burnout from overloads. This danger does not occur in a relay of the above type.

The adjustment is simpler and a greater range of adjustment possible. It is sometimes necessary to change coils of series relays to secure the desired adjustment.

SIMPLE STARTER WITH VOLTAGE-DROP ACCELERATING RELAY

Composition.—There has been recently developed, by one of the manufacturers, a so-called voltage-drop relay, which is somewhat similar to the multi-point relay just described. This relay is illustrated in Fig. 189. It has two coils, termed the calibrating coil and the assisting coil. The former determines the point at which the relay armature will release and thus close a pilot contact. The function of the assisting coil is to supplement the calibrating coil to close the relay. The action

may be considered in connection with a simple starter the diagram of which is shown in Fig. 190.

Operation.—When the line switch is closed, the calibrating and assisting coils of the relay are connected in series across the line and the relay armature is attracted. This opens contact *A* and closes contact *B*. When the starting button is closed, current flows from positive line, through the stop and the start buttons, through the closing coil of line contactor 1 to the negative line. The line contactor then closes and, in so doing, establishes its holding circuit through its auxiliary contact. Closure of the line contactor short-circuits the relay assisting coil and leaves the calibrating coil connected across the starting resistor so that the voltage on the calibrating coil is proportional to the current flowing through the resistor. When the motor is at rest, full voltage exists across the calibrating coil but this voltage decreases as the motor accelerates. At a voltage determined by the calibration, the relay armature releases, closing contact *A*, causing the accelerating contactor to close and short-circuit the starting resistor.

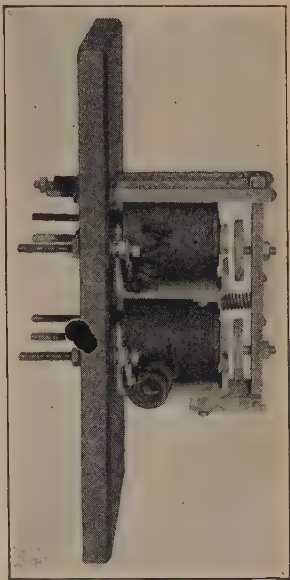


FIG. 189.—Voltage-drop relay.

In more complex controllers a number of voltage-drop relays are required. Thus a reversing controller with several resistor steps will have two voltage-drop relays functioning in connection with the forward and reverse contactors respectively and an additional relay for each resistor step.

This general type of relay does not require mechanical connection with the contactors. Its coils are shunt coils and are thus independent of motor size. Accurate calibration over a wide range is afforded. The relays are grouped on the panel and may be enclosed. The main wiring for the panel is

more direct and simple. It appears probable that relays of the time element, multi-point, voltage-drop or similar types, used in connection with shunt contactors, will generally prevail over types using series coils.

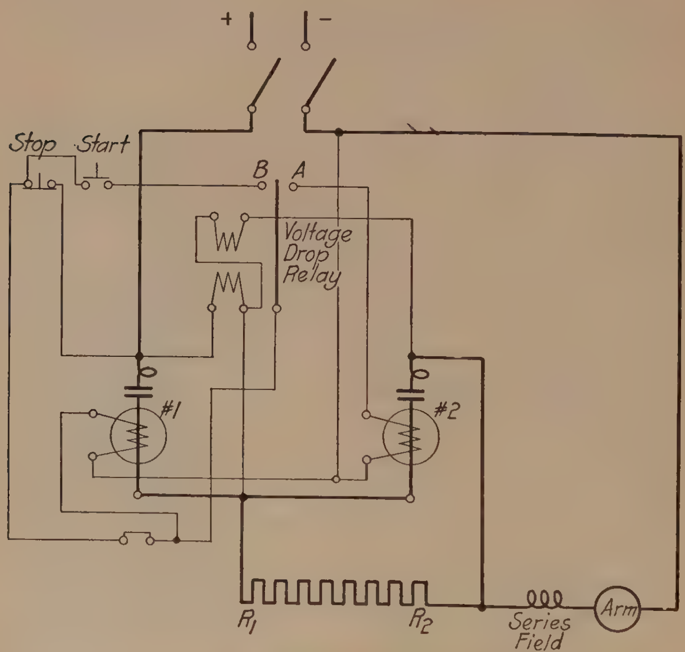


FIG. 190.—Connections for simple starter using voltage-drop relay.

REVERSING CONTROLLER WITH DYNAMIC BRAKING FEATURE

Composition.—A reversing controller with two points of speed control and with dynamic braking on the off position, is illustrated in Fig. 191 and shown diagrammatically in Fig. 192. This controller comprises a line switch and fused control switch for isolating the circuits. The directional contactors are handled by a two-pole unit having a back contact, there being two such units, one for each direction. A line contactor 5 and three shunt accelerating contactors are supplied. A two-coil overoad relay and a voltage relay supply overload and no-voltage protection. The operation is briefly as follows:

Off Position.—The master establishes a circuit from positive line through the coil of the voltage relay to negative, causing the voltage relay to close. A circuit is then established from posi-

Fig. 191.—Reversing controller with dynamic braking on the off position.

tive line through the voltage coil and contact and overload relay to negative line. As this circuit does not include the master the voltage relay remains closed when the master leaves the

off position. The voltage relay opens upon failure of voltage or when the overload relay opens. It is then necessary to

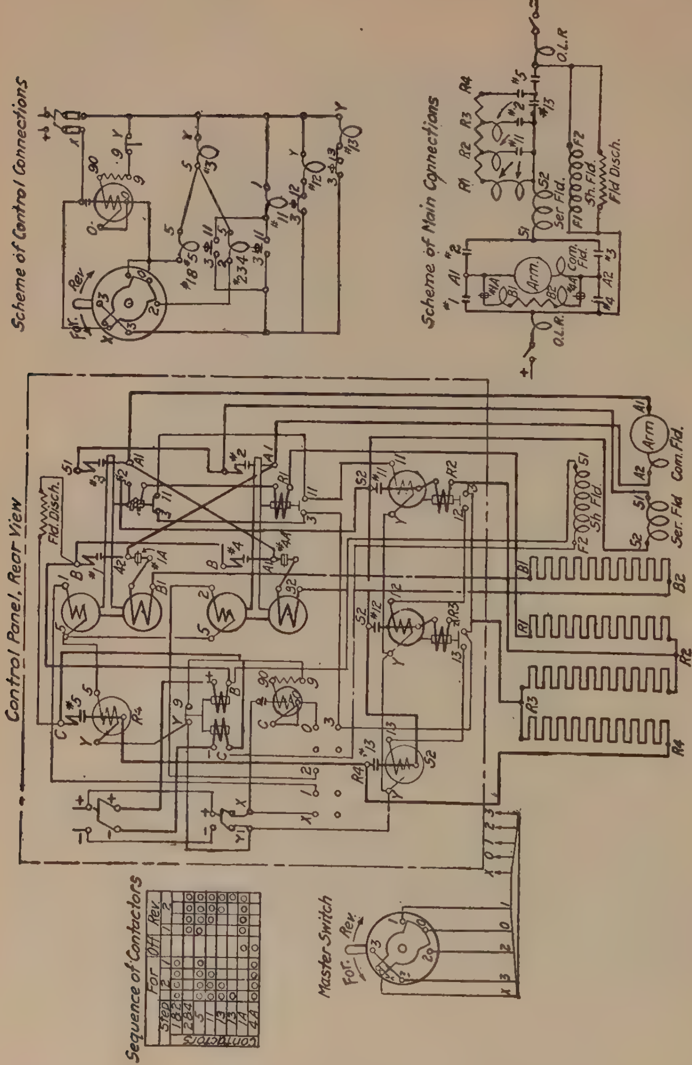


FIG. 192.—Connections for reversing controller with dynamic braking.

return the master to off position to reset the voltage relay.

First Point Forward.—The master completes a connection from positive line through the closing coil for the upper directional unit, breaking the back contact $1A$ and closing directional contactors 1 and 3. This control circuit passes thence through the closing coil for line contactor 5, closing that contactor. The motor circuit is now completed through contactors 1, 3 and 5 and the motor starts with all the accelerating resistor in circuit.

Second Point Forward.—The master now completes a circuit, in addition to the one established on the first point, from positive line through the master and through the contacts of the series accelerating relay on the 1–3 contactor, through the closing coil of shunt accelerating contactor 11. When the series relay drops, completing this control circuit, contactor 11 closes, shunting out the portion R_1–R_2 of the accelerating resistor.

After contactor 11 has closed and the current has fallen off sufficiently to permit the series relay connected with this contactor to drop, a further control circuit is completed through the shunt closing coil of contactor 12. Closure of this contactor short-circuits portion R_2–R_3 of the accelerating resistor. In like manner accelerating contactor 13 closes after contactor 12 has dropped its series relay. Closure of contactor 13 connects the motor across the line.

Reverse.—Starting from rest in the reverse direction is the same as above described for the forward direction except that the directional unit 2–4 closes instead of unit 1–3. This reverses the direction of current flow through the armature.

The two directional contactor units are so interlocked mechanically that both directional elements cannot be closed at the same time, although both back contact elements are free to do so.

Dynamic Braking.—This feature is accomplished by bringing the master to off position while the motor is under speed. This operation opens the directional contactors 1 and 3 and closes the back contactor $1A$, leaving full shunt field on the motor. The armature is short-circuited through the resistor B_1–B_2. The rotation of the armature in the presence of the shunt field causes a voltage, resulting in current flow through

the braking resistor. The armature, acting as a loaded generator, quickly comes to rest.

The armature circuit during dynamic braking period is from the armature through the back contactor $1A$, through the series coil on the back contactor, which seals the contactor positively, through the braking resistor B_1–B_2, through the back contactor series coil and contactor $4A$, back to the armature.

It is to be noted that a dynamic braking controller of this type is suited for use with compound-wound motors only, since the shunt field is depended upon to provide the dynamic braking action. The heavier the shunt field the greater the dynamic braking torque for a given armature current. The braking torque and current may be varied by adjusting the value of the braking resistor B_1–B_2.

While it is possible to reverse the master quickly while the motor is running, high plugging peaks are prevented since the braking current through the series sealing coils holds the directional contactors open, counteracting the effect of the shunt closing coils, until the motor is slowed down sufficiently to permit reversal on straight accelerating resistance without severe peaks.

Overload Protection.—Excess current through either overload relay coil will open that relay, opening the holding circuit of the voltage relay and causing the latter to open. The main contactors then open.

No-voltage Protection.—Upon failure of voltage the voltage relay opens. This relay can be reset only by moving the master to the off position.

REVERSING CONTROLLER WITH SHUNTED ARMATURE

Composition.—A simple reversing controller for a small motor, provided with an armature shunt for a slow speed point, is shown in diagram in Fig. 194. A controller by the same builder but of somewhat different make-up is illustrated in Fig. 193.

This controller comprises four directional contactors 1, 2, 3, 4, mechanically interlocked; a line contactor 5; a shunt

FIG. 193.—Reversing controller with armature shunting feature.

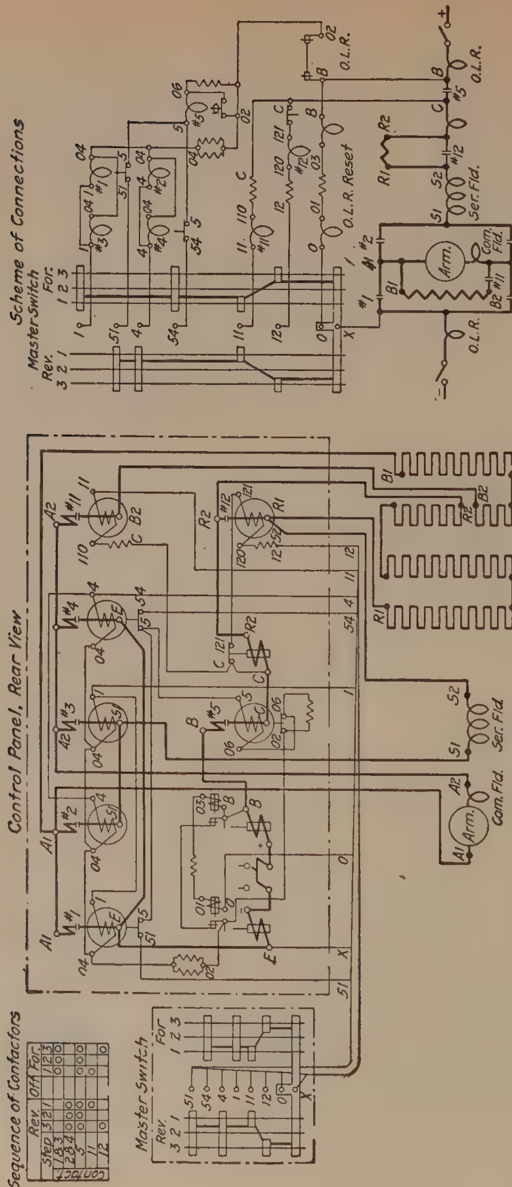


FIG. 194.—Connections for reversing controller with armature shunting feature.

accelerating contactor 12; an armature-shunting contactor 11; two overload relays of the time element trip, magnetic reset type and a small drum-type master switch. The action may be outlined as follows:

Off Position.—All contactors are open. A circuit is made at the master in the off position, energizing the reset magnets of the overload relays so that, if they have been tripped, they will be reset when the master is moved to the off position.

First Point Forward.—Control circuits are completed at the master, energizing the closing coils of directional contactors 1 and 3 and line contactor 5, also armature-shunting contactor 11. When these contactors close the motor starts, at slow speed, with shunted armature and accelerating resistor in circuit.

Second Point Forward.—Conditions remain the same except that the control circuit for contactor 11 is opened at the master, causing that contactor to open. This removes the shunt around the armature and permits the motor speed to increase.

Third Point Forward.—The control circuit for accelerating contactor 12 is completed at the master. If the current relay attached to line contactor 5 has dropped, the closing coil of contactor 12 will be energized. Closure of this contactor short-circuits the accelerating resistor and connects the motor across the line, bringing it to full speed.

Slow-down.—It should be noted that if the master be thrown from the third point to first point, the armature is shunted and the series field strengthened while the armature may be running at fairly high speed. The resulting increase in generated armature voltage will cause rather heavy current flow through the armature shunt, retarding the armature. The action depends materially upon the nature of the load and the resistor values.

Reverse.—The action in the reverse direction is identical with that in the forward direction except that directional contactors 2 and 4 operate, reversing the armature current flow.

Overload Protection.—Two overload relays adjacent to positive and negative lines protect from excess current due to overloads, shorts and grounds. One relay, of the instantaneous trip type, is set at about 250 per cent full load, to protect only against shorts and grounds. The other relay, of the inverse

time element type, is set at about 125 per cent full load to protect primarily against continued overload and secondarily against a ground current from that side of the line. These relays, once tripped, are held open by a catch. It is then necessary to energize the reset coil, to release them.

No-voltage Protection.—This feature is omitted as unnecessary (for the particular application involved).

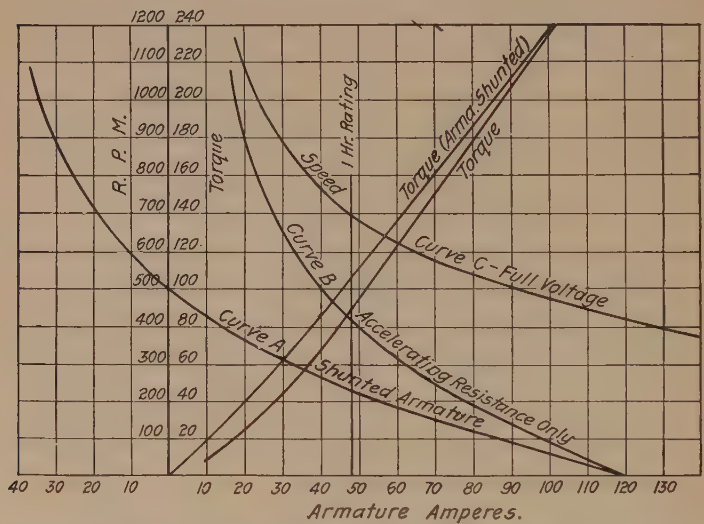


FIG. 195.—Characteristic curves of series motor with resistors in series and shunt with armature.

Comments.—It may be noted that resistor units are used in series with the closing coils of the contactors. This is said to render the contactors more rapid in action.

The curves in Fig. 195 set forth the motor characteristics which are obtained on the different controller points with a 12 hp. series motor. It will be noted that, on the first point (curve *A*) with shunted armature, the speeds at all loads are restricted but more noticeably for the lighter loads. The characteristic is much like that of a compound wound motor. Curve *B* shows the action with the armature shunt removed but with accelerating resistance in circuit. Curve *C* is the motor characteristic. It may be noted that, if the motor is operating

at a good speed, say 800 r.p.m. as indicated on curve C, and if the control is quickly thrown to first point, the armature current will momentarily reverse, as indicated by the corresponding speed point on curve A. The effect of the reverse current is to quickly slow down the armature, along curve A.

Two torque curves are shown. With shunted armature the torque values for a given armature current are somewhat higher than normal due to the stronger field.

CRANE HOIST CONTROL USING SHUNTED ARMATURE

Composition.—The connections for a simple controller employed for crane hoist service are shown in Fig. 196. The controller is similar in appearance to that shown in Fig. 181. This controller is very similar to a straight reversing controller, previously described, except that an armature shunt is used for one direction of rotation. The panel carries four reversing contactors 1, 2, 3, 4. There is a line contactor 5 but this is not employed as a circuit-breaker contactor as the panel has no protective features. A time element type accelerating relay is used, governing two shunt accelerating contactors 11 and 12. A spring-closed contactor 6 serves to close a dynamic braking circuit on the off position of the master. A knife switch serves to open the motor circuit while testing out the contactors. The ordinary accelerating resistors R_1–R_2, are used. In addition, there is a bank A_1–S which shunts the armature when switches 1 and 3 are closed in lowering. The action of the controller may be outlined as follows:

Off Position.—All contactors are open except 6, which is spring-closed. The series brake, being de-energized, is closed.

First Point Hoisting.—The master switch energizes the closing coils of directional contactors 2 and 4 and line contactor 5. The opening coil of contactor 6 is energized, causing it to open. The motor circuit is completed through the armature, series field, series brake and accelerating resistor. The brake releases and motor starts.

Resistor A_1–S is short-circuited by contactor 2 and has no effect.

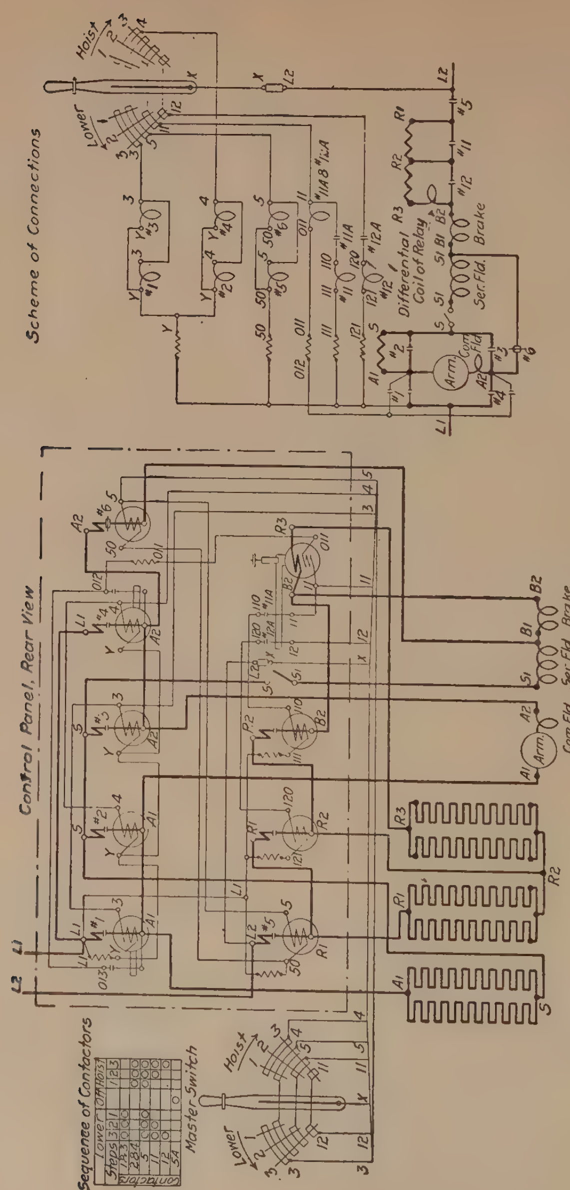


FIG. 196.—Connections for crane-hoist control using armature shunt in lowering.

Second Point Hoisting.—When contactor 4 closes on first point, an auxiliary contactor in this unit is also closed, completing the circuit of the accelerating relay closing coil. This coil is opposed by a series coil which delays its action. Its action is delayed by a dash pot also, giving time element acceleration. The contacts 11*A* and 12*A* of this relay close in succession after time intervals. When contact 11*A* is made, the closing circuit of accelerating contactor 11 is completed. That contactor then closes, reducing the accelerating resistor.

Third Point Hoisting.—The circuit of the closing coil of accelerating contactor 12 is closed at the master. If the accelerating relay has closed the relay contact 12*A*, the accelerating contactor 12 closes, connecting the motor across the line.

First Point Lowering.—The master energizes the closing coils of directional contactors 1 and 3 and line contactor 5. The opening coil of contactor 6 is energized, causing it to open. The motor circuit is completed through the armature, series field, series brake and accelerating resistor. The brake releases and the motor starts to drive the hook downwards. It is to be noted that resistor A_1–S is now shunted around the armature. This passes current which strengthens the series field, thus limiting the speed at which a light hook may be driven downwards. In case of an overhauling load the armature generates a voltage causing a braking current to flow through the armature shunt, restricting the speed.

Second and Third Points Lowering.—The action of the contactors is the same as in hoisting. The effect of reducing the accelerating resistor is to increase the speed, due to increased armature voltage.

Deceleration from Lowering.—As the master is moved to the off position there is no material increase in braking effect until the off position is reached. Contactor 6 then closes. This short-circuits the armature and series field through resistor A_1–S in such a manner that a braking current flows. As the series brake is not included in the circuit it sets and assists in stopping the motor.

Limitations.—This controller is a comparatively simple type for crane-hoist service. It has not the uniformity of speed with varying hook loads nor the flexibility of adjustment or

nicety of speed control in lowering obtainable with more complex types of crane controllers. The single resistor A_1–S serves to limit the driving speed with light hook, to limit the overhauling speed with loaded hook and to limit the braking current in stopping. Its value must compromise the various requirements.

Protection.—No protection is afforded at this controller. A separate "crane protective panel," not shown, is depended upon for overload and no-voltage protection.

CRANE-HOIST CONTROL WITH DYNAMIC BRAKING

Composition.—A typical crane-hoist controller suited to give good speed control with both light and loaded hook, is shown in Fig. 197. The connections are shown in Fig. 198.

The units which comprise this controller are as follows. A knife switch is supplied to disconnect motor and pilot circuits from the line. A fused control switch protects the pilot circuits and enables them to be isolated. Shunt contactor 1 is a directional contactor for hoisting. Shunt contactor 2 is a directional contactor for lowering. Shunt contactor 3 is a directional contactor used on lowering to connect the armature and series field in parallel across the line. Contactor 4 is a spring-closed contactor which short-circuits the armature through the series field on the off position, causing dynamic braking. Shunt contactor 5 is a line contactor to disconnect the motor from the negative line. Shunt contactor 6 serves to cut out resistors in series with the armature on the last point lowering, placing the armature across full voltage for high-speed operation. Shunt contactor 7 serves several functions. In hoisting it acts as an accelerating contactor, closing on the last controller point. In lowering it closes on the first controller point, passing a good current through the armature to give positive downward drive with a light hook. It is open on the second, third and fourth points lowering, introducing resistor R_5–R_6 into the armature circuit to increase the lowering speed with loaded hook. On the last point lowering it closes, giving a high-speed lowering point, with light hook without permitting excessive speed with a

loaded hook. This action is considered further in following paragraphs. Shunt contactors 11, 12 and 13 control the accelerating resistance in hoisting and the series field strength in lowering. There is but one overload relay, this being of the instantaneous trip, magnetically retained type. There are four separate resistor banks. Resistor R_1–R_4 is straight accelerating resistance in hoisting. In lowering, it serves to control the series field strength, hence the speed. Resistor R_{11}–R_{12} is a current-limiting resistor to avoid short-circuiting

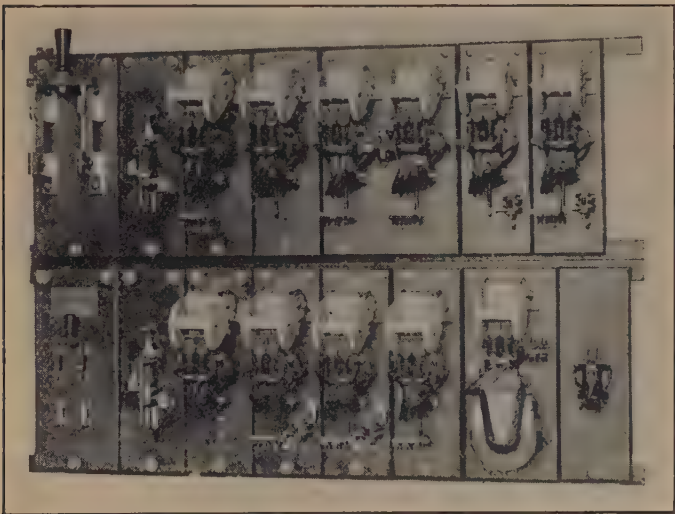


FIG. 197.—Crane hoist controller with dynamic braking lowering.

the series field across the line, on the first lowering points. Resistors R_5–R_6 and R_6–R_7 function together to limit the armature current during both acceleration and deceleration in lowering. Resistor R_6–R_7 serves further to limit the dynamic braking current in stopping while lowering. The action of the controller may be outlined as follows:

Off Position.—Contactor 4 is closed, since it is a spring-closed contactor and its releasing coil is not energized. The armature is short-circuited through the series field and resistor R_6–R_7. This causes dynamic braking from a lowering direc-

tion only since, from the hoisting direction, the braking current flow tends to demagnetize the series field.

Contactor 3 remains closed if the master is brought to off position from a lowering position. The resistor in series with

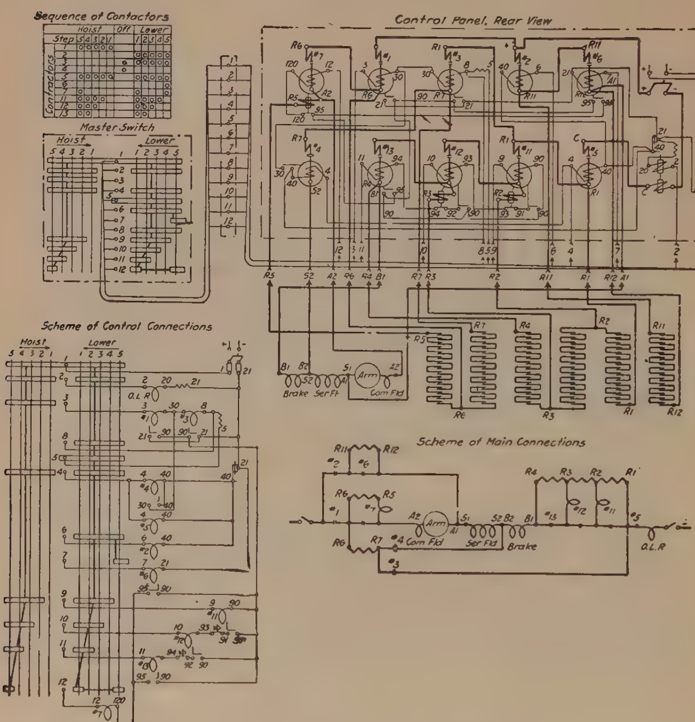


FIG. 198.—Connections for crane-hoist controller with dynamic braking lowering.

the closing coil of contactor 3 and master segment 5 causes only sufficient current to flow through the closing coil to hold it closed provided it has been closed in lowering by being fully energized through master segment 8. The purpose in retaining contactor 3 closed in stopping from lowering operation is because it then completes a braking circuit which serves as a safeguard.

With the master in the off position the series brake is set.

First Point Hoisting.—Braking contactor 4 opens, its opening circuit being completed at segment 4 of the master switch. This removes the shorted path around the armature. Line contactor 5 closes simultaneously with the opening of contactor 4, both being controlled from the same segment on the master. When contactor 4 opens, its auxiliary contact closes, completing the closing circuit of directional contactor 1. Closure of contactors 5 and 1 completes the motor circuit in the hoisting direction.

Second Point Hoisting.—Accelerating contactor 11 closes, its closing circuit being made at master segment 5, and passing through an interlock on contactor 1. Closure of contactor 11 reduces the accelerating resistor. Due to the interlock in the closing circuit of contactor 11 this contactor cannot close unless the directional contactor is closed first.

Third and Fourth Points Hoisting.—Accelerating contactors 12 and 13 close in sequence under the control of the master and restricted also by series relays 11 and 12. As further precaution, interlocks on contactors 11 and 12 are used to insure the proper sequence of closure of these accelerating contactors.

Fifth Point Hoisting.—The closing circuit of contactor 7 is completed at master segment 12. So soon as series relay 7 drops contactor 7 closes. This eliminates the last step of accelerating resistor and connects the motor across the line for full-speed hoisting.

First Point Lowering.—When the master is thrown to first point lowering the first response is the opening of braking contactor 4 and closing of line contactor 5, just as in hoisting. Simultaneously, directional contactor 2 closes. The series field and brake are now energized through the accelerating resistor. When contactor 4 opens, its auxiliary contact closes, completing the closing circuit of contactor 3 from master segment 8. Closure of this contactor puts the armature in circuit through contactor 2, resistor R_{11}–R_{12}, through resistors R_5–R_6–R_7, and through contactors 3 and 5.

When contactor 3 closes it becomes possible for resistor contactors 11, 12, 13 and 7 to close, their circuits being closed at the master and passing through the auxiliary contact of contactor 3. Closure of contactors 11, 12, 13 gives a strong

series field which assists in starting to drive downwards and then restricts the lowering speed. Closure of contactor 7 cuts out resistance in the armature circuit, giving the armature a good starting torque for starting a light hook downwards.

Second Point Lowering.—Conditions remain as on the first point except that contactor 7 opens, introducing resistance in the armature circuit. If a light hook is being driven down, the lowering speed will decrease slightly. If the load is overhauling, the introduction of resistance in the braking circuit causes an increase in speed since the armature may generate a voltage higher than impressed voltage by an amount corresponding to the drop in the armature circuit. For light hook lowering the second point is slower than first point, but, with a loaded hook, the speed on second point is faster than on first point.

Third Point Lowering.—Contactor 13 opens. This weakens the series field and thus causes an increase in speed for all loads.

Fourth Point Lowering.—Contactor 12 opens. This weakens the series field further and causes a further increase in speed.

Fifth Point Lowering.—Contactor 13 opens, weakening the series field further, tending to increase the speed. Contactor 6 closes. This tends to strengthen the series field and thus to offset the effect of opening contactor 13. The voltage impressed on the armature circuit is increased, however, tending to increase the speed. This influence is neutralized in part by closure of contactor 7 which decreases the resistance in the braking circuit, tending to decrease the speed in lowering a load and to increase the speed in driving down a light hook. The result is a fast speed point for a light hook.

Deceleration from Lowering.—In bringing to a stop a load being lowered, the motor is called upon to exert braking action. As the master switch is thrown from an advanced lowering point toward the off position, the resistor contactors 13, 12, 11 close in sequence. One result of this action is the strengthening of the series field. As the armature is revolving rapidly its generated voltage increases. This voltage forces a braking current through the circuit A_1, series field, series brake, resistors R_4–R_1, as in circuit, contactor 3, resistors R_7, R_6, R_5 to A_2. This current further strengthens the series field, so that

the action is cumulative. As the series brake is included in this dynamic braking circuit, it is held open and is not called upon to decelerate the load. When the master reaches the first point, contactor 7 closes, reducing the resistance in the braking circuit by shorting R_6–R_5. When the master reaches the off position contactor 4 closes. The dynamic braking circuit is now from A_1 through the series field, contactor 4 and resistors R_7, R_6, R_5 to A_2. These resistors permit a rather heavy flow of braking current, quickly stopping the armature. As the series brake is not included in the circuit, it is released, helping to bring the load to its final stop and holding it thereafter.

Speed Control.—It is to be noted that several banks of resistors are employed to control the conditions while lowering. By variation of these resistors the performance of the drive may be modified.

Resistor R_{11}–R_{12} is in circuit during the lowering operation only. Its prime function is to limit the voltage impressed upon the series field while R_4–R_1 is shorted and to restrict the impressed armature voltage in starting to lower. Increasing resistor R_{11}–R_{12} decreases the driving torque in starting and decreases the speeds in lowering, particularly with light loads, except on the last point, when this resistor is out of circuit.

Resistor R_1–R_4 is used in both hoisting and lowering operations. This resistor is proportioned for the hoisting service. In cases where a high lowering speed is desired the step R_1–R_2 may be increased to give a weak field point in lowering. This change reduces the torque and current on first point hoisting.

Resistor R_6–R_7 is in circuit only while lowering. It functions to control the lowering speed and to limit the current in braking while lowering. Increasing R_6–R_7 decreases the power torque in starting. It decreases slightly the lowering speed with a light hook and increases materially the lowering speed with loaded hook. It decreases the braking current in stopping. In driving down a light hook the drop in R_6–R_7 is subtracted from armature impressed volts, decreasing armature speed. In lowering a load with braking action the

armature must generate additional voltage by the amount of the drop in R_6–R_7, before it can exceed the voltage impressed from A_1 to R_1 and set up the flow of braking current. This

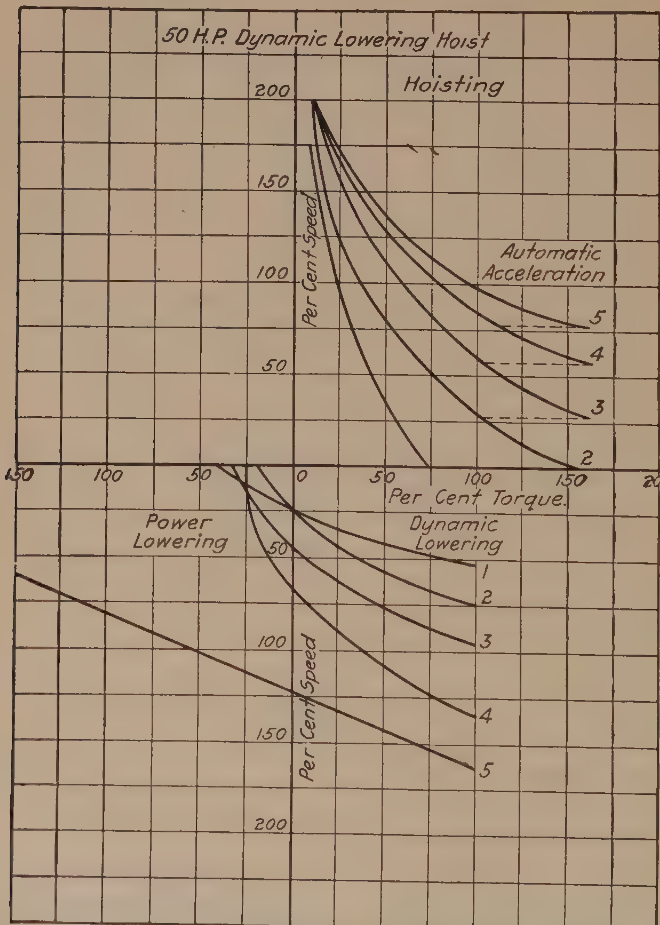


FIG. 199.—Characteristics of crane-hoist control with dynamic braking lowering.

means that the armature will speed up in order to generate the voltage required to give a balanced condition.

Resistor R_5–R_6 acts as accelerating resistance in hoisting. In lowering it functions similarly to R_6–R_7 except that it is

cut out on the first point to give a good starting torque. It is cut out also on the last point lowering in order to give a fast speed for lowering a light hook yet restricting the maximum lowering speed with loaded hook to a safe value. A change in R_5–R_6 has an influence similar to a change in R_6–R_7, except on the first and last points lowering when R_5–R_6 is shorted. By selection of the point of adjustment the action can be restricted to intermediate points or can be made effective for all lowering points, as desired.

Overload Protection.—Overload protection is afforded by one relay on the panel. Operation of this relay opens the circuits of contactors 5, 4 and 2. Contactor 4 in turn affects contactor 1. The motor is thus isolated in any case. When the relay is tripped by the action of the series coil it is held open by the shunt coil until the master is moved to the off position. Protection is provided on this panel by the overload relay in one side of the line. Protection in the other side of the line is afforded in advance of this control at a so-called crane protective panel, not shown.

No-voltage Protection.—This protection is not provided, being cared for by the protective panel mentioned above.

Figure 199 shows the characteristics of operation of a crane-hoist controller similar to that discussed above. Distances above the origin represent hoisting speeds; distances below the origin represent lowering speeds. Distances to the right of the origin represent torques in hoisting direction; those to left of origin represent torques in lowering direction. It is to be noted that the lowering curves show values for driving downward light loads as well as for restraining heavy loads. The several curves show the operation upon the various resistor steps.

TIME ELEMENT CONTROLLER WITH PILOT MOTOR

Composition.—A controller utilizing a pilot motor to drive a cam shaft to operate the accelerating contactors is illustrated in Fig. 200. A diagram of a similar controller, somewhat simplified, is shown in Fig. 201. This is shown for a motor running in one direction only. The panel carries one line contactor, an

overload relay, two relays *A* and *B* and the pilot motor, cam shaft and contactors actuated by the cams thereon. The sequence of closure of these contactors is determined by the angular setting of the cams.

Operation.—When the "start" button is depressed, it completes the circuit of the closing coil of relay *A*, which then establishes a holding circuit for itself.

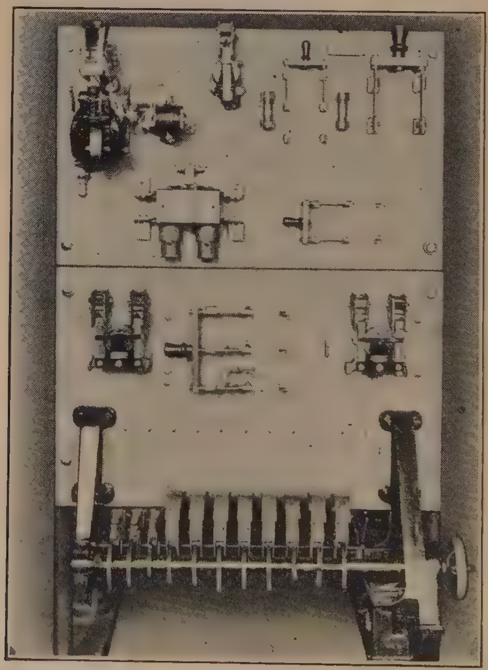


FIG. 200.—Non-reversing controller with pilot motor acceleration.

Closure of relay *A* completes the circuit of the pilot motor through contact *C* and also through the interlock of contactor 1, this interlock being closed when contactor 1 is open. The pilot motor starts the cam shaft into rotation. Auxiliary contactor *E* is among those closed by a first position cam. This contactor remains closed for all running positions and requires the pilot motor to complete the accelerating cycle. This motor continues to run until the final running position is reached, when auxiliary contactor *C* opens and causes the pilot motor to stop.

The rotation of the cam shaft also closes auxiliary contact *D* on the first point. This completes the coil circuit of relay *B*, causing it to close. The coil circuit of line contactor 1 is completed when relay *B* closes. When contactor 1 closes, the main motor starts. Incidentally a maintaining circuit for relay *B* is made by one of the interlocks on contactor 1.

Closure of relay *B* also causes a resistor to be shunted around the armature of the pilot motor, causing it to slow down during the period of acceleration of the main motor.

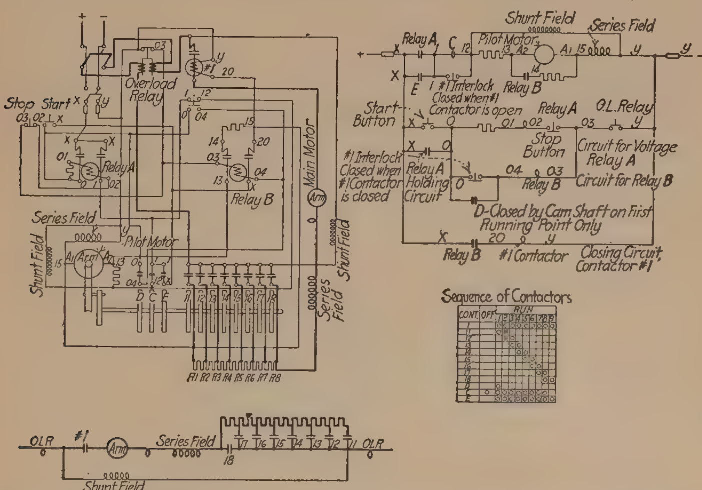


FIG. 201.—Connections for non-reversing controller with pilot motor acceleration.

As the pilot motor revolves the cam shaft further, the resistor short-circuiting contactors 11, 12, 13, etc., close in sequence until the main accelerating resistor is all cut out and the main motor is operating on full voltage.

If the "stop" button is depressed, it causes relay *A* to open. This, in turn, opens relay *B*, which, in turn, causes line contactor 1 to open. If the "stop" button is depressed while the main motor is accelerating, the pilot motor will continue to revolve the cam shaft and complete its cycle although the opening of line contactor 1 nullifies the effect on the main motor.

When contactor 1 opens, its upper interlock closes, completing the pilot motor circuit through auxiliary contactor *E*. This causes the pilot motor to revolve the cam shaft to the off position, at which point auxiliary contact *E* is opened.

Characteristics.—The acceleration obtained with this type of controller is of the time element classification. The timing can be adjusted by adjustment of the speed of the pilot motor. This is accomplished, in the controller described, by adjustment of resistors in series and in shunt with the armature. As already noted, the armature is shunted only while the cam shaft is rotating through the angle corresponding to the acceleration period for the main motor.

The time element obtained by this type of controller is more accurate and stable than that obtained by a dash pot relay and it is subject to finer control. The control, particularly the main circuit, is comparatively simple. A large number of accelerating points can be obtained with simplicity and compact arrangement.

There are many variations of this general type of controller. In some cases a face-plate with pilot motor operated contact arm is used instead of the cam shaft shown. In some cases a drum replaces the cam shaft, pilot circuits being controlled by the drum, these in turn actuating separate magnetic contactors or other devices.

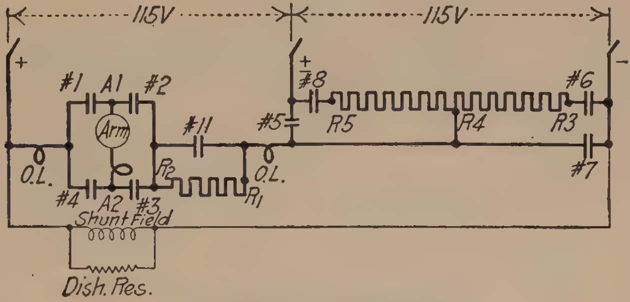
Among the common applications of this general type of control may be mentioned large printing presses. Here the pilot motor may be more closely governed by the operator to give creeping speeds, inching and speed control by armature and field resistance. Such controllers are ramifications of the simple principles here outlined.

REVERSING CONTROLLER FOR USE ON A MULTIPLE-VOLTAGE SYSTEM

The main circuit connections for a simple reversing controller for use on a multiple-voltage system are shown in Fig. 202. This is of interest principally with reference to the method used in accelerating and transferring from one voltage to another without interrupting the armature circuit. The principal units

of this controller are the directional contactors 1, 2, 3, 4, the accelerating contactor 11 and the transfer contactors 5, 6, 7 and 8.

Operation.—On the first step in either direction, the armature is connected across half voltage in series with accelerating resistor R_1–R_2. This is accomplished through closure of directional contactors 1 and 3, or 2 and 4, according to direction, and also contactor 5. On the second step the accelerating resistor



Contactor	Forward 6	5	4	3	2	1	Off	Reverse 1	2	3	4	5	6
1	O	O	O	O	O	O							
2								O	O	O	O	O	O
3	O	O	O	O	O	O							
4								O	O	O	O	O	O
5				O	O	O		O	O	O			
6		O	O	O						O	O	O	
7	O	O										O	O
8		O	O	O						O	O	O	
11	O	O	O	O	O				O	O	O	O	O

Steps Nos. 2 and 6 are running points

Fig. 202.—Main connections of a reversing multiple-voltage controller.

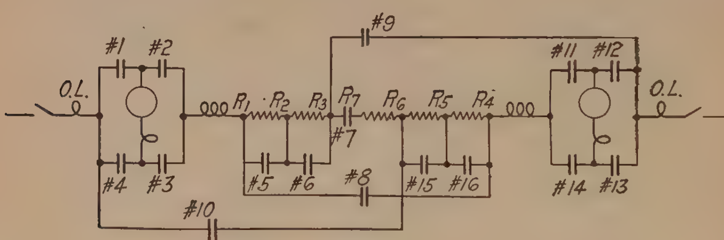
R_1–R_2 is cut out through closure of contactor 11. The armature is now subjected to half voltage.

Closure of 6 and 8 contactors on the third step places resistor R_3–R_5 in circuit but does not influence the motor. When contactor 5 opens on the fourth step, one side of the armature is connected to R_4. This point now has a potential about midway between R_3 and R_5; thus the armature has impressed upon it about three-quarters of full-line voltage. On the fifth step contactor 7 closes and short-circuits resistor R_3–R_4. The motor is now across full-line voltage. On the sixth step contactors 6 and 8 open, removing resistor R_3–R_5 from circuit.

This diagram is illustrative of a principle which may be modified or expanded as required. Elevator controllers operating on four-voltage systems, namely, 60, 120, 180, 240 volts, are arranged to function in the general manner shown, the same transfer method being repeated in changing from one voltage to the next until the armature is across full-line voltage.

SERIES-PARALLEL CONTROLLER WITH NON-INTERRUPTED TRANSITION

An interesting control layout for series-parallel operation of two series motors is shown in Fig. 204. The principal feature



Contactor	Forward										Off	Reverse									
Step	10	9	8	7	6	5	4	3	2	1		1	2	3	4	5	6	7	8	9	10
1	O	O	O	O	O	O	O	O	O	O											
2												O	O	O	O	O	O	O	O	O	O
3	O	O	O	O	O	O	O	O	O	O											
4												O	O	O	O	O	O	O	O	O	O
11	O	O	O	O	O	O	O	O	O	O											
12												O	O	O	O	O	O	O	O	O	O
13	O	O	O	O	O	O	O	O	O	O											
14												O	O	O	O	O	O	O	O	O	O
5	O	O			O	O	O	O	O				O	O	O	O	O			O	O
15	O	O			O	O	O	O						O	O	O	O			O	O
6	O				O	O	O								O	O	O				O
16	O				O	O										O	O				
7					O	O	O	O	O	O		O	O	O	O	O	O				
8				O	O												O	O			
9	O	O	O	O														O	O	O	O
10	O	O	O	O														O	O	O	O

FIG. 203.—Diagram of series-parallel magnetic controller showing transition without interruption.

of interest is the transition from series to parallel operation without interruption of the main current and torque. The controller comprises two sets of directional contactors 1, 2, 3, 4, 11, 12, 13, 14, accelerating contactors 5, 6, 15, 16, series contactors 7 and 8 and parallel contactors 9 and 10.

Operation starts with the two motors in series and with all

of the accelerating resistors in circuit. The latter is cut out in steps by contactors 5, 15, 16, 16 and 8 closing in sequence. On the seventh step, parallel contactors 9 and 10 close but have little influence on operation other than to cause current flow in the accelerating resistors R_1–R_3 and R_4–R_6. As soon as parallel contactors 9 and 10 close, interlocks on these contactors cause the series contactors 7 and 8 to open. The motors are then in parallel and with accelerating resistors R_1–R_3 and R_4–R_6 in circuit. These are cut out on steps 9 and 10. All the steps on this controller may be running points except step 7 which is on the same point as step 8, two separate steps being indicated to show the method of transition clearly.

CHAPTER XVI

THE PRINCIPLES OF ALTERNATING-CURRENT CONTROL

TO START AND ACCELERATE THE MOTOR

Most alternating-current motors, like those for direct current, are designed primarily with a view to running performance. To provide proper conditions during the starting interval, a controller is necessary. The control requirements differ with the motor type. The following motors will be considered:

- Single-phase motors;
- Polyphase motors;
  - Squirrel-cage induction motors;
  - Wound-rotor induction motors;
  - Synchronous motors.

SINGLE-PHASE MOTORS

Small single-phase motors are of several types, series motors and shunt induction motors being the more common. It is desirable for the sake of simplicity that motors of small size be started by merely connecting them to the service lines. Series motors are well suited to this purpose. Induction motors are adapted to this method of starting by means of split-phase windings, self-contained. Motors up to $\frac{1}{3}$ hp. rating, designed in this manner, may be thrown directly upon the power lines with no ill effect. Induction motors of larger size are commonly equipped with a split-phase starter. These motors have multiphase primary windings. The split-phase starter serves to supply out of phase current to the different phase windings of the motor creating a revolving field about the stator similar to that produced in a multiphase motor.

A diagram of a split-phase starter is shown in Fig. 84, Chap. VIII. These motors develop only moderate starting torque and require rather heavy starting current. Repulsion motors and combination designs are built capable of connection directly across the power lines in sizes up to about 5 hp. Rheostatic starters are supplied with some of the larger motors, to reduce starting currents.

Special types of repulsion-induction motors are designed for reversing or varying speed service. Some of these motors depend upon brush-shifting for their control, a shifting lever being mechanically connected to the brush yoke of the motor. Other types require drum controllers, which reverse portions of the stator winding to reverse the rotation and insert resistance in the stator and rotor circuits to increase and decrease the motor speed.

It is obvious that any motor which may be started by closure of a simple switch may also be started by automatic circuit-closing devices such as contactors, relays, pressure or vacuum switches, thermostats and the like. Many single-phase motors are so controlled.

POLYPHASE MOTORS—THE SQUIRREL-CAGE INDUCTION MOTOR

Starting with Full Primary Voltage.—When voltage is applied to the primary windings of a polyphase induction motor, the revolving field, traveling at synchronous speed, is set up instantly around the air gap. As the rotor is at standstill, the rotor slip is high. The revolving flux cuts the rotor conductors rapidly and sets up in them a relatively high voltage. The current which flows in the rotor conductors due to this voltage is restricted only by the rotor resistance and reactance. The heavy current thus set up in the rotor causes a large current to be taken by the primary, due to transformer action.

A standard squirrel-cage induction motor, connected directly across full voltage, will draw from 500 to 700 per cent rated full-load current and will develop 125 to 175 per cent full-load torque. This inrush of current is only momentary and the current falls rapidly as the motor attains speed. The magnitude of the first

rush of starting current depends upon electrical factors only and is independent of the mechanical motor load. The duration of the starting peak, however, depends upon the time required for acceleration, which, in turn, depends upon the mechanical load.

Squirrel-cage motors of the high-resistance rotor type, such as are used for elevator service, will take about 250 to 300 per cent rated full-load primary current and develop about 150 to 200 per cent full-load torque if connected directly to full voltage. Motors of this class have a slip of about 15 per cent at full load.

Starting with Reduced Primary Voltage.—As a current five to seven times normal is too severe upon the motor and lines and the resulting starting impulse too sudden, it is necessary to reduce this effect. This can be done, in the case of the squirrel-cage motor, only by reducing the impressed primary voltage. The exact values of starting currents and torques produced with different impressed voltages depend upon the motor characteristics. The following values are typical, however, for standard squirrel-cage motors:

TABLE I

INDUCTION MOTOR STARTING PERFORMANCE

Impressed voltage. Per cent rated volts	Starting current input to motor. Per cent full-load current	Starting torque. Per cent full-load torque
100	600	175
90	550	150
80	480	110
70	420	80
60	360	60
50	300	40

Starting Transformers.—Reduced voltage for use in starting squirrel-cage motors may be provided in several ways. Where transformers are used for the power supply of one or more motors it is possible to take off reduced potential from taps in the secondary winding. Additional leads are run from these

taps. The controller merely provides for switching, first to the low voltage taps, then to full voltage lines. If standard transformers are used, a starting voltage of 50 per cent full voltage may be readily provided. At this voltage the motors will develop about 40 per cent full-load torque at starting. This is insufficient in many instances but is satisfactory in some cases. By means of special taps in the transformers a higher starting potential may be provided and better torques obtained from the motors. This method of securing reduced starting

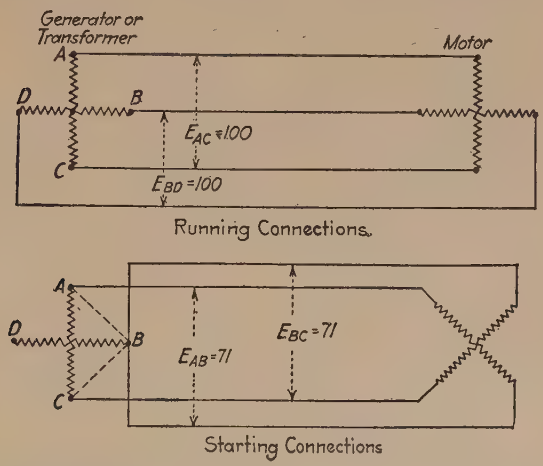


FIG. 204.—Connections for induction motor on interconnected two-phase circuit to obtain reduced starting voltage.

potentials is not extensively employed but it offers possibilities of considerable saving in cost of controllers where conditions are favorable. It is quite commonly employed where transformers are provided to supply single units as in the case of large synchronous motors or converters started by induction motor action from the alternating-current side.

Where a two-phase interconnected power system is used, a starting voltage 71 per cent of line voltage may be obtained by interconnecting the phase leads, as indicated in Fig. 204. A double-throw starting switch or controller is necessary. No extra power supply lines are necessary.

A reduced potential for starting squirrel-cage induction motors may be obtained by providing small transformers for each motor, together with means for connecting the motor first to a reduced potential taken from the transformers and then to the lines. Either polyphase transformers or a combination of single-phase transformers may be used. These transformers commonly take the form of autotransformers, to reduce their cost. Starters operating on this principle are called auto-

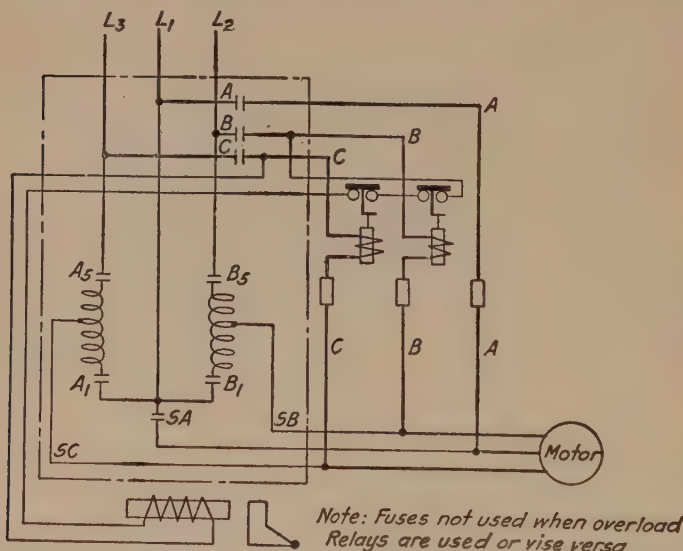


FIG. 205.—Connections for auto-starter with two-coil autotransformer.

starters or starting compensators. It is customary to provide the autotransformers with several taps so that various starting voltages may be secured. Polyphase transformers may have either two or three coils. For two-phase motors two coils only are necessary. For three-phase motors two coils may be employed, connected open delta, or three coils may be used, being connected in star or Y. Figures 205 and 206 show the main connections for three-phase compensators connected according to these two schemes. Where single-phase transformers are used they are combined to obtain the equivalent result.

It is to be noted that, when autotransformers are used, the

line current is less than the motor primary current in a degree depending upon the ratio of transformation. This condition will be readily seen by inspection of Fig. 207.

Primary Resistance Starting.—Reduction of impressed voltage may be secured by insertion of resistors in series with the primary windings of the motor. The amount of resistance may be adjusted to secure the desired starting voltage and

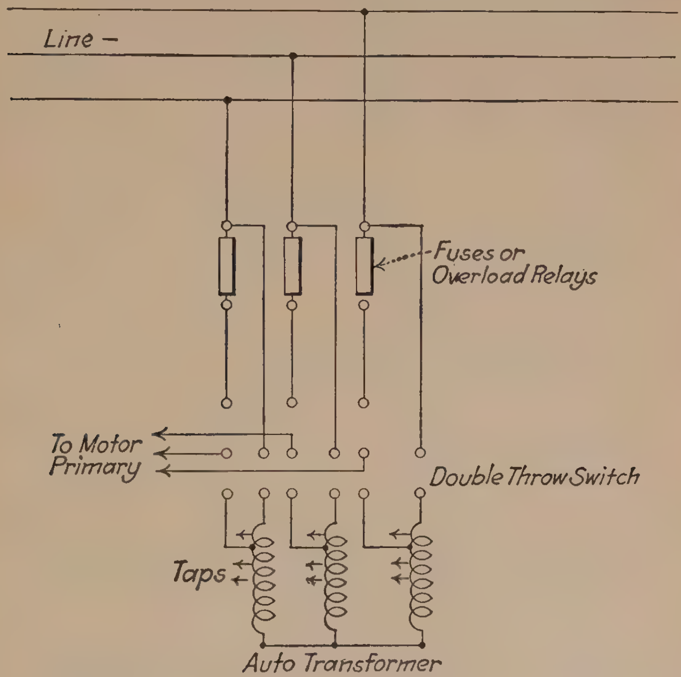


FIG. 206.—Connections for auto-starter with three-coil autotransformer.

torque. As the motor attains speed, the resistors may be cut out by short-circuiting in one or more steps. This method differs distinctly from the autotransformer method in that the latter causes a reduced voltage of constant value to be impressed on the motor whereas the voltage at the terminals of a motor in series with primary resistors varies according to the motor current. The initial current inrush causes a large drop in voltage through the resistors and the motor voltage is then relatively

low. As the motor accelerates, the current input decreases, the voltage drop in the resistors decreases and the motor voltage is thus automatically increased. If the load is not heavy, it is possible to accelerate nearly to synchronous speed before the starting resistors are short-circuited. The primary resistance starter has the marked advantages of simplicity, low first cost and easy repair. It is not necessary to interrupt the circuit to transfer from starting voltage to full voltage and the interruption of torque development is therefore avoided. It has the

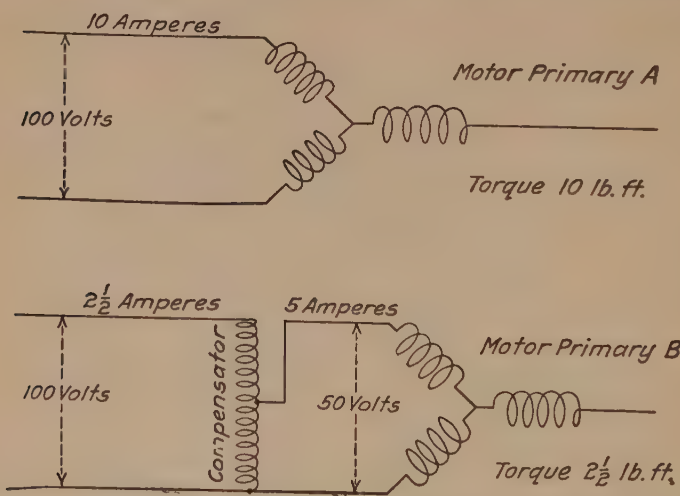


FIG. 207.—Induction motor starting current with and without starting transformers.

disadvantage of lower efficiency and larger current intake from the line, since motor current and line current are the same with this type of starter. It also has the disadvantage that an exceptional torque demand, which calls for increased current, causes increased resistance drop and decreased impressed voltage just when ample voltage is necessary. Partly because of the high line current taken, primary resistance starters have not been extensively used except for the smaller motors.

For three-phase service, resistors may be inserted in two or three lines. For two-phase service, resistors are inserted in each phase. The method of calculating the primary resistance

may be explained with the use of Fig. 208. Knowing the starting torque required, the starting voltage necessary may be determined from motor characteristics, bearing in mind the fact that the torque is proportional to the square of the primary voltage. Let us assume that it is desired to apply 50 per cent voltage with the motor at standstill. With the average squirrel-cage motor, the inrush current, when 50 per cent voltage is applied at starting, is about 300 per cent normal and the power factor at starting is about 50 per cent. Let E_1, Fig. 208, represent line voltage. Since the motor power factor at starting is 50 per cent, the motor voltage E_m may be laid off as indicated.

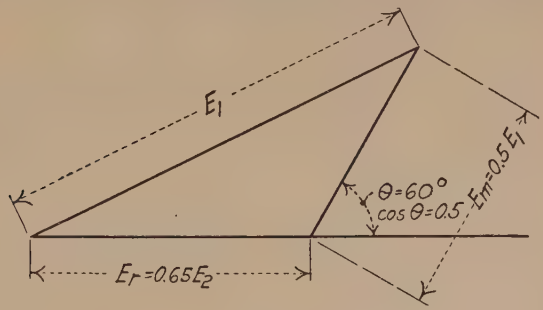


FIG. 208.—Diagram for determination of primary resistance.

cated. The angle θ is 60 deg. since the cosine of 60 deg. (equals power factor) is 0.50. The voltage drop across the primary resistance will be E_r, which in this case equals 65 per cent of E_1. The resistance per phase will then be the voltage across the resistance, E_r, divided by the current. For three-phase it is necessary to introduce the constant 1.73 because of the phase difference of line voltage and current. The resistance

$$R=\frac{E_r}{I\times 1.73},$$

where I = line-current inrush;

R = resistance per phase.

Since, in this case, $E_r = .65E_1$,

$$R=\frac{.65E_1}{I\times 1.73}.$$

If resistance is inserted in only two phases, the above value of R must be increased 50 per cent.

Star-delta Connection.—It is possible to utilize a double connection of the motor primary windings to provide reduced starting potential. The primary windings of a three-phase motor may be brought out with both ends of each phase ending in a terminal at the motor. The six resulting terminals are connected to a double throw switch, usually of a modified drum

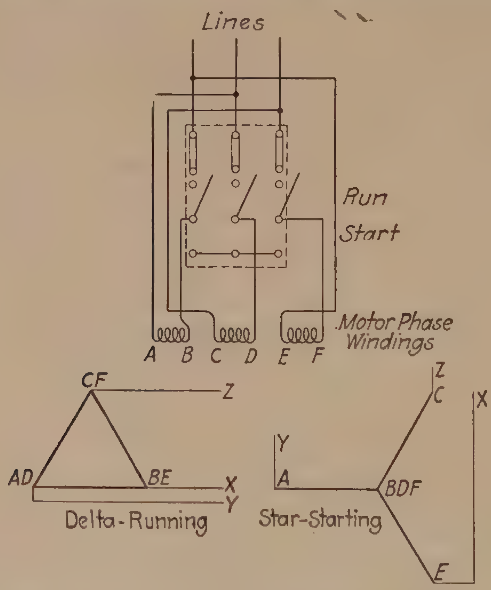


FIG. 209.—Star-delta starting of three-phase induction motor. Connections and voltage relations.

type. The connections of this switch are such that, for the starting position, the line voltage is impressed upon the motor coils connected in star or Y, while, for the running position, the motor windings are connected in delta across the line. The voltage impressed upon each phase winding star-connected at starting is thus 58 per cent of the voltage impressed upon the windings delta connected for the running position. The starting current is proportionately reduced. This method is illustrated in Fig. 209, showing connections and voltage relations.

A disadvantage incident to this so-called star-delta starting method lies in the fact that the starting voltage can have but one value, namely 58 per cent of line voltage. Where the torque required for starting is at all heavy, this low voltage may prove insufficient. Another disadvantage lies in the necessity of winding the motors for delta connection for line voltage. There are some advantages for the Y connection which can-

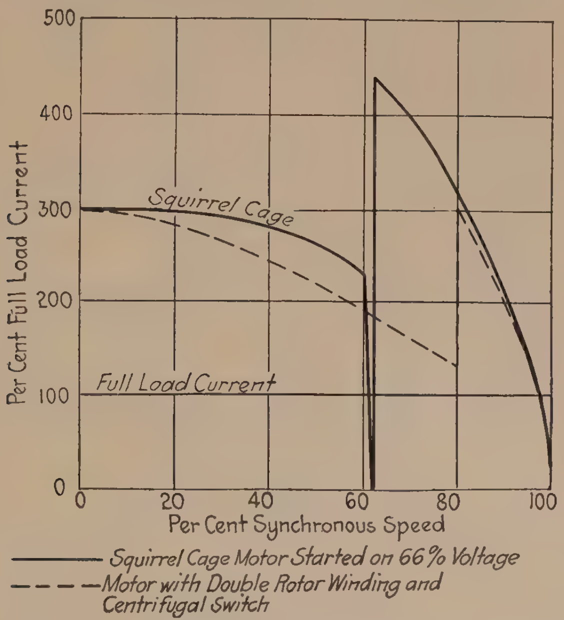


FIG. 210.—Current input during acceleration of squirrel-cage and "automatic start" induction motors.

not be realized if this starting method is used. The advantage of the method lies in the simplicity and low cost of the starting device.

Starting Current and Torque.—The current and torque conditions incident to the starting of a squirrel-cage induction motor with auto-starter may be visualized by inspection of Figs. 210 and 211, respectively. It will be noted that when 66 per cent voltage is impressed on this motor, approximately 300 per cent current flows and about 80 per cent of full-load

torque is developed. As the motor speed increases, the current falls off but the torque increases, due primarily to decreasing rotor frequency and impedance, as explained in Chap. V, page 57. The figures indicate the transfer to full voltage as occurring at 62 per cent speed. Both the current and torque are greatly increased when full voltage is applied. If the motor reaches a higher speed before transfer to full voltage, these peaks are reduced. The dotted lines indicate the action of a

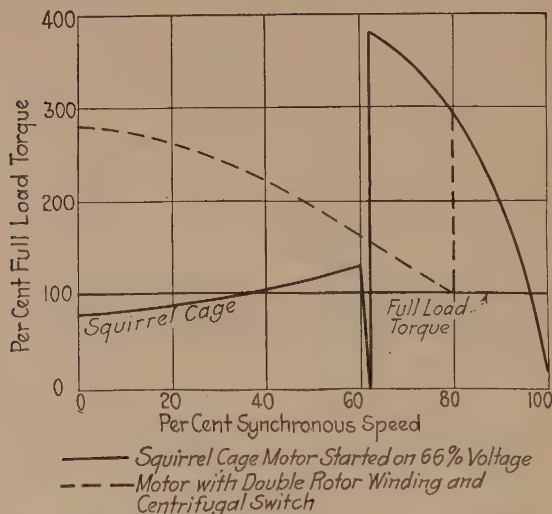


FIG. 211.—Torque developed during acceleration of induction motors.

motor with double rotor winding and centrifugal governor, as described in Chap. V, page 74.

WOUND-ROTOR INDUCTION MOTOR

Starting with Secondary Resistance.—The characteristics of an induction motor are so affected by its secondary circuit resistance that excellent starting performance may be secured from motors so constructed that their secondary circuit resistance may be varied during the starting period. The wound-rotor induction motor has its rotor windings brought out to slip-rings. External resistance of any desired value may be connected between these rings. The external resist-

ance may be varied at will. By this means it is possible to limit both starting current and torque to desired values. After the motor has started the resistance may be adjusted to secure the desired running conditions.

The conditions which govern the starting performance of a wound-rotor type of induction motor may be most readily observed by inspection of the characteristic curves of a motor of this type. Figure 34, Chap. V, gives a typical set of curves showing the relations between torque, speed and primary current with various values of secondary resistance.

In starting a motor we deal first with the conditions at zero speed. It will be noted that curve *A*, showing a condition of low secondary resistance, indicates a standstill torque about equal to full-load motor torque and a corresponding primary current (with full primary voltage) of about six times full-load value. As soon as some speed is attained the torque increases and the current rapidly decreases. This condition is comparable to the starting condition for the squirrel-cage type of motor. Curve *B* shows that an increase in secondary resistance produces greater torque at standstill with lesser primary current. Curves *C* and *D* show further improvement until, with resistance as of curve *D*, we secure maximum or pull-out torque of the motor with a current about four times full-load value. If we increase the secondary resistance still further, as shown by curve *E*, the torque at standstill decreases, the maximum torque now occurring at negative speed corresponding to a "plugging" condition. The primary current at standstill has also decreased. Curve *F* shows that, by insertion of sufficient secondary resistance, it is possible to secure full-load torque at standstill with approximately full-load primary current input.

The above curves all show conditions existing with full voltage impressed upon the primary winding of the motor but with the secondary resistance varied. Since it is possible to control the starting performance of motors of this type so excellently by adjustment of the secondary resistance there is no need for the reduction of the impressed primary voltage during the starting period. The primary winding is therefore connected directly across the line. The control for a

wound-rotor type of induction motor must care for both primary and secondary circuits. It must provide a means for connecting and disconnecting the primary winding from the source of power and it must provide a means for varying the secondary resistance.

Determination of Secondary Resistance.—In order to calculate the secondary resistance for a wound-rotor induction motor, the locked-rotor volts and full-load secondary amperes must be known. If only the locked-rotor voltage is known, the full-load secondary current may be found by use of the formula:

$$I_r = \frac{\text{H.P.} \times 746}{E_s \times 1.73 \times (1 - \text{slip})},$$

where I_r = full-load secondary current;
H.P. = rated horsepower of the motor;
E_s = locked secondary volts;
slip refers to that at rated speed with full load.

The general procedure in the determination of secondary resistance for a wound-rotor induction motor is similar to that for direct-current motors, outlined in Chap. XI. The allowable primary current inrush is determined, taking into consideration the torque demanded by the load. The secondary resistance supplied is somewhat greater than that giving maximum torque at standstill. Thus the starting condition is exemplified, in general, by regulation curve E or F, Fig. 34, Chap. V, page 56. In Table II are shown approximate values of torques developed for various initial primary current values.

A formula for determination of Y-connected balanced three-phase secondary resistance for wound-rotor induction motors, is given below.

$$R = \frac{E_s}{1.73 \times I_r} \times \left(\frac{100}{T_1} - 0.10\right),$$

where R = external resistance per leg of the Y, ohms;
E_s = locked secondary volts;
I_r = full-load secondary current;
T_1 = torque developed on first point of controller, expressed in per cent of full-load torque.

The expression $-\frac{0.10\times E_s}{1.73\times I_r}$ is included as a deduction for resistance and reactance of rotor winding and leads.

Based on this formula, the following resistance values are obtained:

TABLE II

VALUES OF THREE-PHASE Y-CONNECTED SECONDARY RESISTANCE

Primary current inrush, first point. Per cent full-load current	Starting torque developed. Per cent full-load torque	R = resistance per leg of Y, ohms
50	30	$1.87\frac{E_s}{I_r}$
70	50	1.10 "
100	100	0.52 "
150	150	0.33 "
200	200	0.23 "

The secondary resistors for wound-rotor motors are usually Y-connected. Sometimes the delta connection is used in order to reduce the current handled by the controller fingers. If the resistors are delta-connected, determine the proper value of Y-connected resistance and multiply by 3 to get the proper resistance of each leg of the delta. The current in each leg of the delta-connected resistors is the motor secondary current divided by 1.73.

The principles governing the subdivision of resistors into steps are similar for direct- and alternating-current motors. The principles outlined in Chap. XI, page 236, may be employed in connection with wound-rotor induction motors. Figure 212 is of interest in showing the similarity between the direct-current motor and the wound-rotor induction motor in accelerating characteristics. This figure shows the torque developed during acceleration of a wound-rotor induction motor with the secondary resistor cut out in three steps. The values of primary and secondary current for any torque value are shown, these being independent of the secondary resistance. A little study will show that, in starting from rest, a primary current of 38 amp. is taken; this falls to 23.5 amp. as the motor acceler-

ates. The first section of the resistor is then short-circuited and the primary current increases again to 38 amp. and falls off again with further acceleration until the next section of the resistor is short-circuited, when the current falls to 23.5 amp., etc. The similarity to Fig. 113, Chap. XI, should be evident.

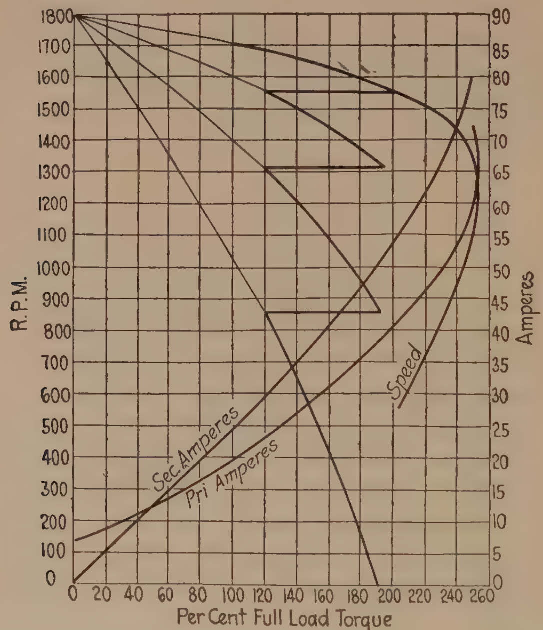


FIG. 212.—Torque developed during acceleration of a wound-rotor induction motor. Secondary resistor cut out in 3 steps.

Where a wound-rotor induction motor is subject to plugging service, an additional external resistor is desirable to reduce the plugging torque and current, just as with the direct-current motor.

It is sometimes desired to start a wound-rotor induction motor with one secondary lead open-circuited and resistance across the other two leads. The resistance is then cut out in steps in one phase at a time. This arrangement is shown in Fig. 255, Chap. XIX, page 423. It has the advantage of an increased number of steps with a minimum number of control

contacts but has the disadvantage of unbalanced current intake, which is particularly pronounced on the last points of the controller.

If single-phase secondary starting is employed the torque developed with given current input is reduced to about one-half that obtained with balanced three-phase secondary resistors. Conversely, the primary current input required to develop full-load torque with single-phase secondary is about 167 per cent of that necessary with balanced three-phase secondary.

Resistor values to be used for single-phase secondary starting duty may be taken from the following table:

TABLE III

VALUES OF RESISTORS FOR STARTING WITH SINGLE-PHASE SECONDARY

Primary current inrush, first point. Per cent full-load current	Starting torque developed. Per cent full-load torque	R = resistance per leg of Y, ohms
84	30	$0.95\frac{E_s}{I_r}$
117	50	0.54 "
167	100	0.24 "

This method of starting should not be employed when more than full-load starting torque is desired, due to the heavy starting current taken.

The Eddystat.—A device termed an "eddystat" controller has been recently developed in England for use in connection with wound-rotor induction motors. This controller derives its name from the fact that it dissipates the secondary losses during acceleration in the form of eddy-current losses, just as the ordinary resistance type of controller uses up the surplus energy as ohmic loss in resistors. The eddystat controller has no moving parts. It consists of three solid steel cores and insulated copper windings with taps, the windings being connected across the motor collector rings. On starting the motor, the rotor current, of line frequency, produces high eddy-current losses in the solid magnetic circuit. As the motor

speeds up, the secondary voltage and frequency decrease and consequently the eddy-current losses decrease automatically. In plugging, the secondary frequency and voltage are nearly double standstill values. The secondary losses are thus increased in proportion and a braking influence is obtained. This controller may be used with reversing motors, only primary switching equipment being required, the secondary action being automatic. As the eddystat controller is always in the secondary circuit the motor is automatically protected. The controller is provided with radiating fins to dissipate the heat.

SYNCHRONOUS MOTOR

Starting by Auxiliary Motor.—The synchronous motor, as its name implies, is operative only at synchronous speed. At standstill it has no torque produced by synchronous motor action. It is necessary to accelerate motors of this type to approximately synchronous speed before they become operative as synchronous motors. If this is done by means of an auxiliary motor or another unit, the control for the synchronous motor becomes merely a means for switching the synchronous motor onto its system when the condition of synchronism is reached, together with means to indicate this synchronous condition and means to control the direct current for the fields.

Self-starting Synchronous Motor.—The so-called "self-starting" synchronous motor secures its starting effort entirely by induction motor action. Self-starting synchronous motors are provided with a squirrel-cage winding on the rotor. This winding is employed to transform the motor, during the starting period, into a modified squirrel-cage induction motor. To start a motor of this type it is the common practice to connect its primary or stator winding across a reduced potential just as is done in the case of the squirrel-cage induction motor. This reduced voltage may be secured by any of the methods employed in providing reduced starting voltages for induction motors. The control for a synchronous motor of the "self-starting" type comprises: a means for connecting the primary first across a reduced voltage and then across full voltage; a means for connecting the fields across resistance during the

starting period and to their direct-current source after the motor has accelerated; a means for adjusting the motor field strength; instruments and protective features as required.

Referring to Fig. 70 in Chap. VII, it may be noted that the current inrush of a slow-speed 60-cycle synchronous motor is relatively low, even with full voltage impressed at starting. This is due to the relatively high impedance of the slow-speed motor. It has been found entirely feasible, in many cases, to connect motors of this class directly to the line and dispense with the partial voltage and transfer provisions. This simplifies the control materially.

TO CONTROL DIRECTION OF ROTATION

Rotation Determined by Revolving Field.—The direction of rotation of a polyphase induction motor, of either squirrel-cage or wound-rotor type, and that of a synchronous motor as well, is governed by the direction of rotation of the revolving field about the stator bore. This revolving field is set up by currents, out of phase with each other, passing through coils so located that the flux travels around the stator as the coils are successively energized. It is evident that a certain sequence of currents passing through a given sequence of coils will cause the flux to travel in one manner. A different sequence of currents, passing through the same sequence of coils, will cause the flux to travel in a different manner. Interchange of two primary leads of a three-phase motor causes the currents in the coils of these two phases to reach their crest values at interchanged periods with reference to the crest current in the third phase. This reverses the direction of travel of the flux from coil to coil, reversing the direction of the revolving field. Reversing the revolving field causes the rotor to follow behind the revolving field in the reverse direction. To reverse the rotation of a three-phase motor it is only necessary to interchange any two of the three primary leads. To reverse a two-phase motor the two primary leads of either phase must be interchanged.

Reversing Duty.—The great majority of induction motors and nearly all synchronous motors are operated in a single direction determined at the time of installation. Direction of

rotation is then merely a matter of connections. Some induction motors are called upon to run in reverse direction only occasionally, as for a backing-off operation. In such cases some type of throw-over switch is commonly installed to reverse the primary leads while the motor is at rest. It is then started in the reverse direction in a normal manner. Actual "reversing duty" is required of but a small minority of induction motors. Ordinary squirrel-cage motors are not adapted to this service. Reversing duty is more commonly handled by the use of wound-rotor motors, the control including switching equipment for reversing the primary leads and means for controlling the secondary resistance, the two functions being so interlocked that full secondary resistance must be in circuit when the primary is reversed.

It may be noted, at this point, that, in reversing a wound-rotor motor, only the primary leads need be interchanged. The rotor circuits are entirely independent and are related to the primary only through the medium of the revolving field. The rotor circuits are self-contained closed circuits; reversal of phase rotation does not affect the action of the secondary resistors. They will function equally well with the revolving field rotating in either direction around the stator bore.

Reversing duty may be successfully handled by specially designed squirrel-cage motors having high rotor resistance. The control comprises a primary switching device for reversing connections, together with means for supplying reduced primary voltage during reversal and acceleration. This type of control is little used except where simplicity of wiring is of advantage, as in the case of traveling cranes.

TO CONTROL THE DIRECTION OF TORQUE

Positive and Negative Torque.—The torque of an induction motor is ordinarily exerted in the direction that the revolving field rotates. If the load overhauls or tends to drive the motor above synchronous speed the motor becomes an induction generator and exerts a negative torque against the direction of rotation and against the revolving field. If a motor be "plugged" by reversal of the primary leads while the rotor

is in motion, the direction of rotation of the field is reversed. The motor exerts a negative torque against its motion until the rotor comes to rest, following which it immediately reverses and tends to accelerate in the direction of the revolving field.

Dynamic Braking.—Dynamic braking, which consists in providing a negative or a restraining torque to bring a motor to rest, cannot be accomplished with the induction motor as simply as with the direct-current motor. It is accomplished by disconnecting the motor primary from the alternating power and exciting the primary winding with a low-voltage direct current. This may be obtained from a suitable direct-current source or from an exciter mechanically connected to the motor. The effect is to create a stationary magnetic field in the stator bore. As the closed circuited rotor revolves through this field a voltage is generated within it, setting up currents which react to produce a torque opposing rotation, through simple generator action. The stronger the fixed flux the greater the braking torque. The lower the resistance in the rotor circuit, the greater the current flow and the greater the braking toroue. This subject is treated more at length in Chap. XXIII.

TO CONTROL THE SPEED OF ROTATION

The speed of rotation of a synchronous motor is constant and cannot be varied except through variation of frequency of the circuit from which the motor is operated.

The induction motor is also primarily a constant-speed machine. It does not lend itself to speed adjustment nearly so well as the direct-current motor. For a restricted range of applications the speed may be so controlled as to meet the requirements of the drive. The various methods of speed control of induction motors are treated at length in Chap. VI. They may be reviewed briefly at this point.

Variable Frequency.—It is possible to vary the speed of an induction motor by varying the frequency of the circuit upon which it operates. This requires that the generator speed be varied or that a frequency changer be employed. The voltage should be varied as the frequency is changed as an increase in frequency has indirect influence similar to a decrease in voltage.

If the voltage be varied with the frequency, the motor will develop approximately constant torque and its horsepower capacity is roughly proportional to the speed. As motors are commonly operated on circuits of fixed frequency, this method is not applicable for extensive use.

Multi-speed Motors.—The rate of rotation of the revolving field of an induction motor is determined by the number of poles per phase in the stator or primary winding. By changing the coil connections, the number of poles per phase may be doubled. The synchronous speed is then halved. In some motors two primary windings are provided in the stator, wound to give a different number of poles. The synchronous speed of the motor then depends upon the winding used. These so-called "multi-speed" motors are usually of the squirrel-cage type. They then require a reduced potential starting device and some type of throw-over switch for changing primary connections. If the motors are of the wound-rotor type, both primary and secondary connections must be changed. A rather complex throw-over switch is then required, together with means for varying the secondary resistance.

Secondary Resistance Control.—The speed regulation of an induction motor depends upon the resistance in the secondary circuit. The greater the secondary resistance the greater the slip below synchronous speed with a given load. By introducing resistance in the secondary circuit of a wound-rotor motor a range of speed down to 30 to 50 per cent below synchronous speed may be obtained. The characteristics are analogous to those of the direct-current motor with armature control. The controller may be of any type capable of adjusting the secondary resistance. Since the motor speed, for a given value of secondary resistance, varies with the load, the speeds may be called varying rather than adjustable. This type of motor and speed control is suitable only where the load is comparatively steady, where speed regulation is not important or where continuous manual adjustment is possible. In proportioning the resistance it is necessary that the load characteristics be known so that the proper amount of resistance may be supplied to obtain the desired speed range. In many cases the load decreases as the speed decreases, requiring rela-

tively higher resistance to secure the desired speed reduction.

Primary Resistance Control.—The slip of an induction motor under load varies approximately inversely as the square of the applied primary voltage. It is therefore possible to control the speed of a squirrel-cage induction motor by changing the primary voltage applied at its terminals. Standard squirrel-cage motors are not suited for this work as their torque, with reduced voltage, is comparatively low. Specially designed

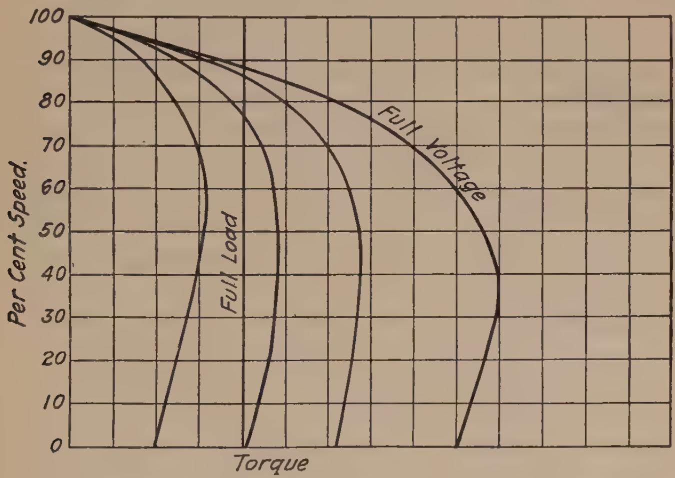


FIG. 213.—Speed-torque curves of induction motor with varied primary voltage.

motors, having low magnetic leakage and high rotor resistance, may be successfully controlled by this method over a limited speed range. The characteristics are similar to those secured by secondary resistance control, the speed varying with change of load. The amount of slip, with a given load, is varied by changing the primary voltage. This may be done by transformers with taps or by means of primary resistors.

Inasmuch as motors adapted for this method of speed control must have a comparatively high rotor resistance, it follows that, even with full primary voltage, there will be considerable slip. Motors of this type will run at 85 to 90 per cent of synchronous speed under full load with full primary voltage.

Figure 213 shows the characteristics obtained by this method at different values of primary voltage. At full voltage the slip is 11 per cent at full load.

Due to the high rotor resistance the secondary losses in a motor of this type are comparatively high. The motor must therefore be conservatively rated or used only for intermittent duty. The main advantages are its simplicity of wiring and absence of collector rings and brushes.

Cascade Sets.—Induction motors may be operated in series-parallel or cascade to provide a selection of speeds. In this arrangement one motor must be of the wound-rotor type. The second motor may be connected to the secondary of the first motor. If both motors are connected for the same number of poles, operation in series or cascade will give a half-speed point. The motors may also be operated singly or in parallel to give full speed. The control for a cascade set is similar to that for the individual motors with additional switches for connecting the secondary of the first motor either to resistors or to the primary of the second motor.

Auxiliary Machines in the Secondary Circuit.—The speed of a wound-rotor induction motor may be decreased over a range from about 30 per cent above to 30 per cent below synchronism by connecting in the secondary circuit, auxiliary machines which introduce a counter-voltage and govern the slip of the rotor. The control for installations of this type is a combination of that for the individual units and comprises a means for starting the main motor by means of secondary resistors, together with an arrangement for throwing the secondary connections onto the auxiliary machines, and switches and rheostats for controlling the auxiliary machines.

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CHAPTER XVII

STARTERS AND CONTROLLERS FOR ALTERNATING-CURRENT MOTORS

The principles underlying the action of alternating-current motors and controllers have been previously outlined. The control requirements differ according to motor size and type.

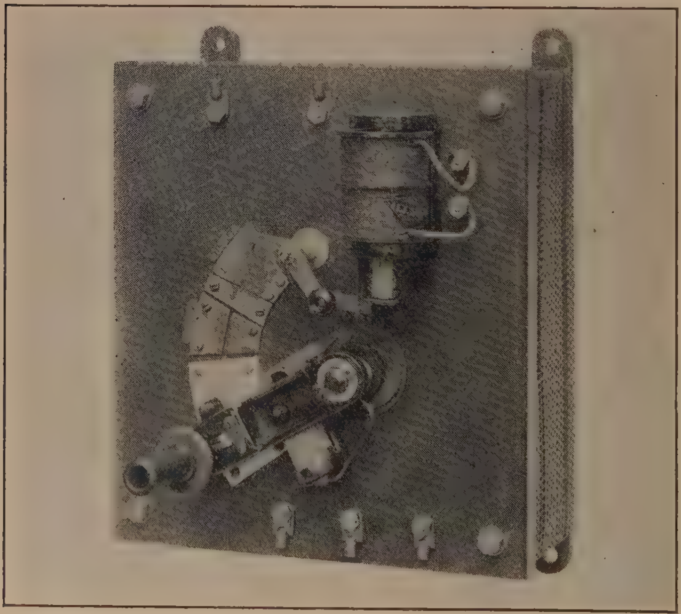


FIG. 214.—Split-phase starter for single-phase induction motor.

The equipments available will, therefore, be considered as applying for single-phase motors and for polyphase induction motors of the squirrel-cage and wound-rotor types respectively.

SINGLE-PHASE MOTORS

Induction Motors.—Single-phase induction motors are commonly built in sizes from 1 hp. to 15 hp. They do not ordinarily include a split-phase winding such as is employed to render fractional horsepower induction motors self-starting. More commonly, a polyphase stator winding is supplied and an external split-phasing device employed to supply out-of-phase currents for starting. The principles of action and the connections for this scheme have been previously set forth in Chap. VIII. Figure 214 illustrates a face-plate type of starter for single-phase induction motors, working on this principle. In appearance, this starter is quite similar to the ordinary direct-current face-plate starter.

Repulsion Motors.—Single-phase motors of the repulsion types are more commonly started by connection direct to the line through a switch or circuit-breaker. For the larger sizes, accelerating resistors may be supplied to reduce the current peaks. A starter for this purpose resembles quite closely the direct-current face-plate type hand starter.

POLYPHASE SQUIRREL-CAGE MOTORS

Simple Switches.—The smaller polyphase induction motors are nearly all of the squirrel-cage type. Squirrel-cage motors of 2 hp. and 3 hp. sizes are sometimes started by a multi-pole fused knife switch, connecting them directly across the line. This method is simple and inexpensive but leaves much to be desired in safety and protective features. Motors of 5 hp. and $7\frac{1}{2}$ hp. sizes are sometimes provided with a multi-pole double-throw knife switch, one side fused, as shown in Fig. 215. The switch is first closed on the unfused side and then on the fused side. This is done to by-pass the fuses during the starting operation so that they may be light enough to protect the motor from overloads. This method also leaves much to be desired. If the operator throws to the running side too quickly he will likely blow the fuses. He is then tempted to replace them with larger fuses and destroy his protection. Not infrequently the fuse in one phase blows, leaving the other fuses intact. The

motor continues to run single-phase and overheats. Many a motor has been burned out in this manner. In case of a power interruption the switch remains in the running position unless opened by the operator. Upon return of power the fuses are then quite sure to blow.

Safety-switch Starter.—To overcome the shortcomings of ordinary knife-switch starters, a number of devices have been used. A safety-switch type, with cover removed, is shown in Fig. 216. The mechanism is enclosed in a cabinet, an external handle being provided. Fuses are depended upon for overload protection. To by-pass the fuses during the starting

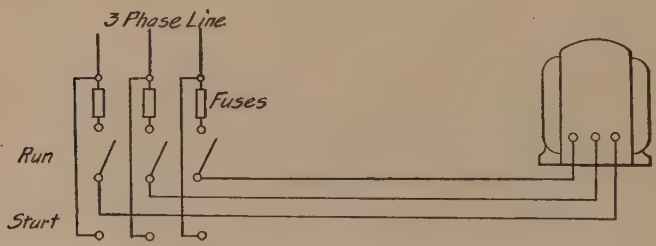


FIG. 215.—Double-throw knife-switch starter for small squirrel-cage induction motor.

interval an ingenious mechanism is employed, causing the switch to close first on the by-pass contacts and then on the fused contacts. A no-voltage trip feature is included. The connection scheme is illustrated in Fig. 217.

Circuit-breakers.—Circuit-breakers have a number of features adapting them for use in starting polyphase squirrel-cage motors. They may be equipped with overload coils in two of the phase leads so that an overload on any phase will open the breaker and disconnect all phases from the line. This prevents single-phase running. The overload protection may be arranged with time element feature to prevent opening of the breaker during the starting interval. Circuit-breakers may also be equipped with under-voltage trip coils so that the breaker will trip upon failure of power, affording "no-voltage protection." This feature may be employed in connection with push buttons, to trip the breaker and stop the machine

from remote points. Circuit-breakers to be used for this service should generally be enclosed and externally operated. Even then, they may lack the ruggedness required for many industrial applications.

FIG. 216.—Combinations starting switch for small polyphase-induction motor.

Oil Switches.—Oil circuit-breakers have been developed in small sizes for starting small polyphase motors. Fig. 218 illustrates a device of this type. The mechanism is entirely enclosed, the contacts being submerged in oil. A no-voltage protection feature is included and two overload relays are provided to protect the motor. These relays are of the inverse time element type so that ordinary starting currents will not trip the switch. The trip mechanism is operative independ-

ently of the handle so that the protective features cannot be defeated by blocking or tying the handle.

Starting on Full Voltage.—It is standard practice to start squirrel-cage motors, in sizes to 5 hp. inclusive, by connecting to full line voltage with some type of starting switch. This practice is also permissible for larger motors providing the starting duty is light, the driven machine capable of sustaining the shock and the high current peaks not objectionable. It

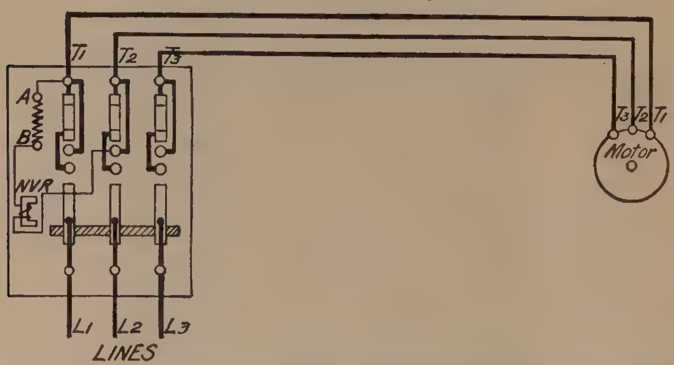


FIG. 217.—Connections for combination starting switch for small polyphase induction motor.

is advisable, however, not to exceed a limit of 10 hp. except as an emergency measure.

Starting on Reduced Voltage.—The majority of squirrel-cage motors are started by connecting them to a reduced primary voltage during the starting interval. This voltage may be obtained by the use of primary resistance or by transformer methods previously outlined in principle. The primary resistance method is not commonly employed for direct, manual starters.

Auto-starters or Compensators.—Starters for squirrel-cage induction motors operating upon the transformer principle are commonly termed auto-starters or starting compensators. They comprise three essential elements, namely: transformers to provide reduced voltage; switching means to connect the motor first to reduced voltage, then to full voltage; protective features. A common type of auto-starter is illustrated in Fig. 219. A core type three-phase air-cooled transformer is provided,

equipped with several taps in each phase for selection of starting voltage. The transformer is Y-connected. The switching arrangement comprises a rocker shaft with contact fingers and flexible leads. This portion of the outfit is submerged in oil. In order to prevent throwing the motor directly across the line, an interlock is provided acting on the rocker switch to make it necessary that the handle be thrown to starting position before it may be thrown to running position. A no-voltage trip fea-

Fig. 218.—Oil switch type of "across the line" manual starter for small induction motor.

ture is regularly provided. Overload protection may be secured, either by use of fuses or by means of relays acting upon the no-voltage trip. These fuses or relays are by-passed during the starting interval. Connection diagrams for two auto-starters were shown in the previous chapter.

Oil Switch Type.—Not all auto-starters are equipped with self-contained transformers. In the larger sizes it is more common to provide oil switches working in connection with separate transformers. The transformers may be either air-cooled or oil-cooled, the former being more common. In some cases the autotransformers may be omitted altogether, the

Fig. 219.—Starting compensator for polyphase squirrel-cage induction motor.

reduced starting voltage being taken from taps of the power transformers feeding the motor. Protective features, as required, are provided to act on the oil switch.

Figure 220 illustrates an equipment utilizing three separate oil switches for magnetizing, starting and running circuits, these switches being operated double throw by two handles. Figure 221 shows the connection diagram. Figure 222 is the diagram of a similar equipment using two separate oil switches. Figure 223 is the diagram of a large double-throw single-unit oil switch employed for the same purpose.

Automatic Compensators.—The manually operated auto-starter has limitations which, in some cases, may prove to be serious drawbacks. The operator must be trusted to afford the proper time interval for acceleration with the handle in the starting position. In case the fuses blow or the overloads trip the operator may tie or block the starting handle in the starting position. Like all manual devices, it is subject to abuse. It must be located convenient to the operator. Being

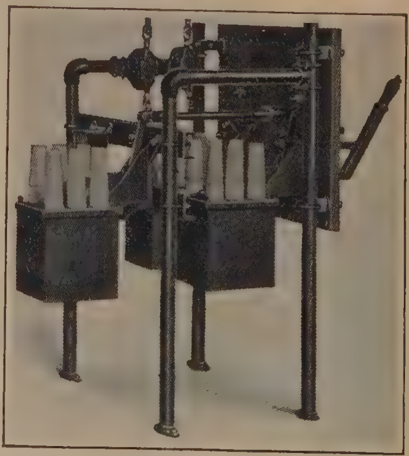


Fig. 220.—Oil switch starting combination for squirrel-cage induction motor.

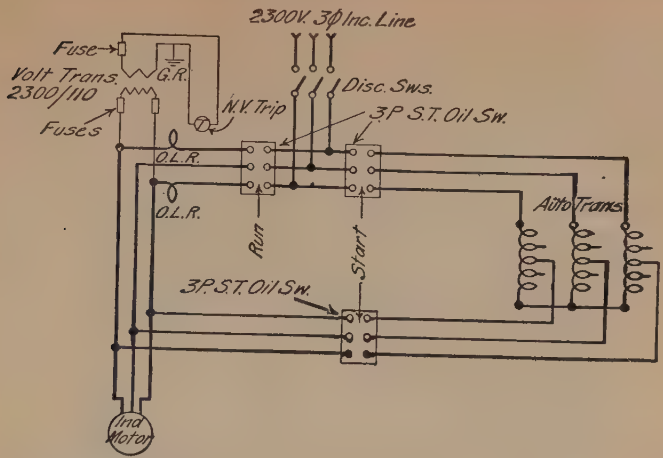


FIG. 221.—Connections for three oil switch starting combination for squirrel-cage motor.

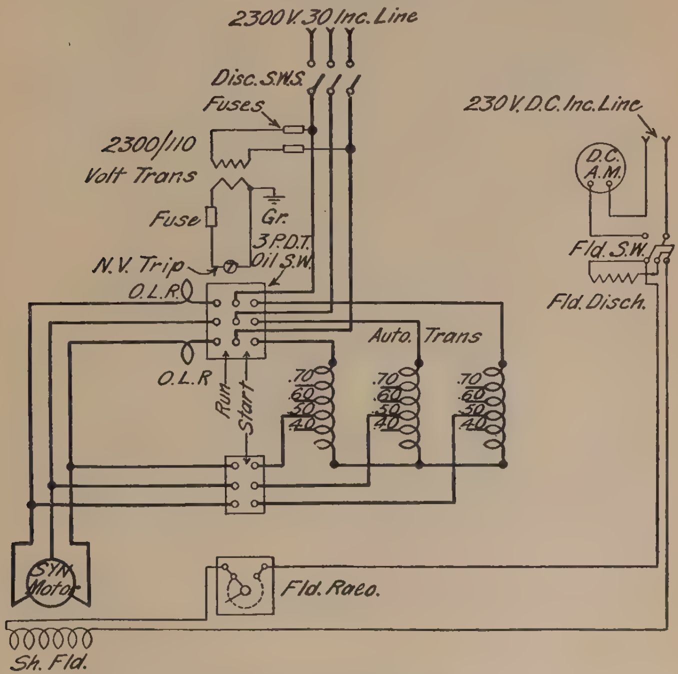


FIG. 222.—Connections for two oil switch starting combination, shown for a synchronous motor.

comparatively bulky, it may prove an obstruction or may be exposed to damage. Being of a direct, manual type, it requires that wiring for the full motor current be run to it and from it. Particularly on the higher voltage systems, a manually operated switching device of this character introduces some hazard to the operator. To overcome some of these disadvantages, so-called "automatic compensators" have been developed. These

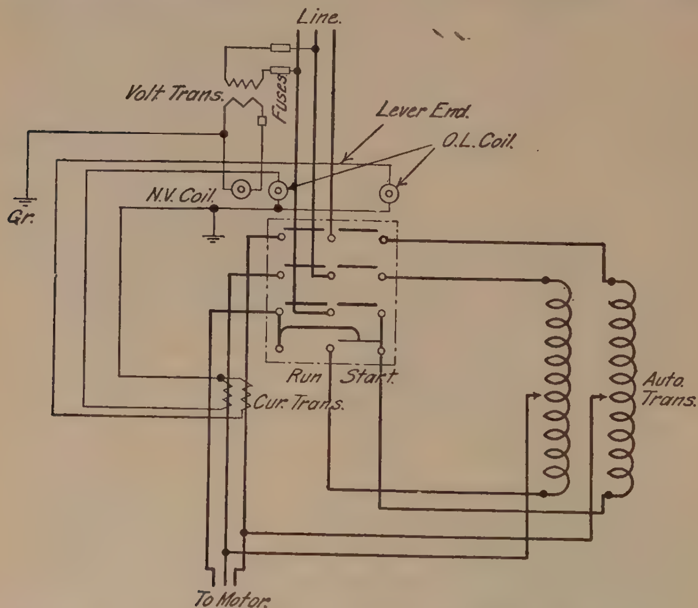


FIG. 223.—Connections for double-throw oil switch auto-starter for squirrel-cage motor.

are similar in principle to the manual types but are magnet-operated.

One equipment of this type is illustrated in Fig. 224. This device includes a two-coil, open-delta-connected autotransformer mounted in the lower part of a frame. Above this is mounted a solenoid with its armature connected to a toggle mechanism, for making the connections. A transition relay working on the current-limit principle is located at the left. This serves to transfer a rocker switch bearing the contact fingers, from the starting position, on the transformer, to the running position,

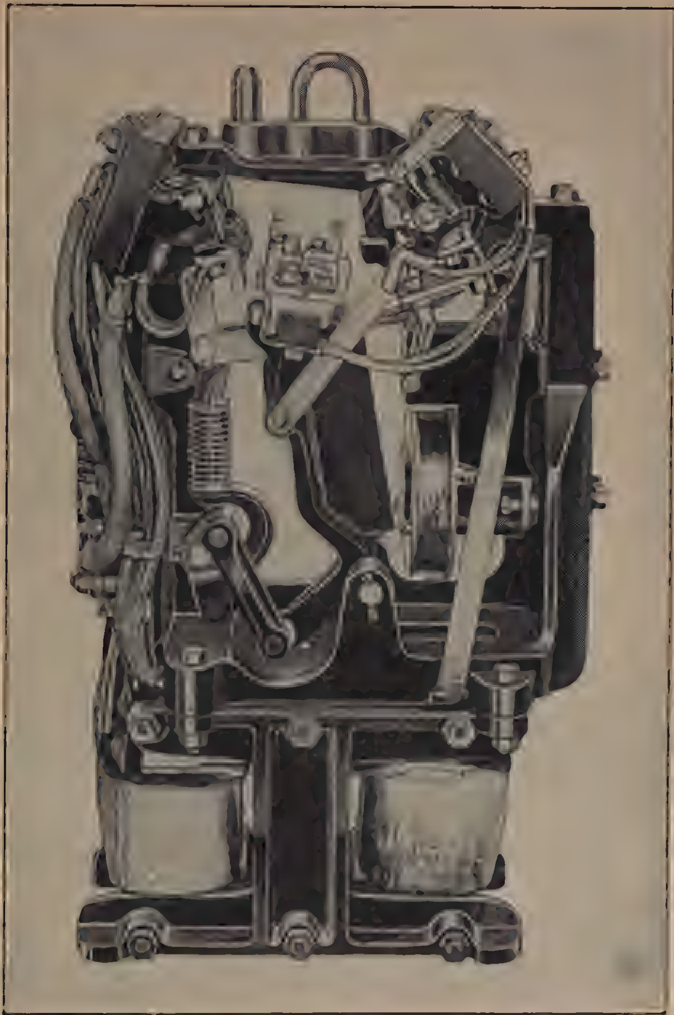


FIG. 224.—Automatic compensator for squirrel-cage induction motor, cover removed.

on the line. The entire frame and mechanism is enclosed and submerged in a tank of oil. Control is by push-button or automatic contacting device. Protection is afforded by a protective panel connected ahead of the compensator. The connections of the entire equipment are shown in Fig. 225.

Another "automatic compensator" is shown, partially exposed, in Fig. 226. The connections are shown in Fig. 227. This device resembles closely the manual auto-starter or compensator except that it is magnet-operated. This equipment operates on the time element principle. The control station

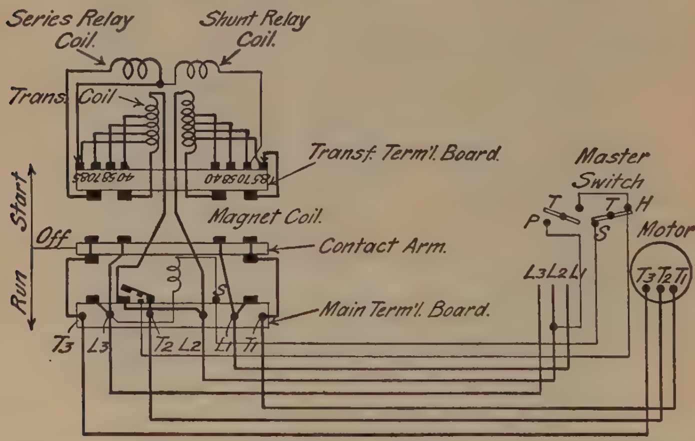


FIG. 225.—Connections for automatic compensator for squirrel-cage induction motor.

embraces a spring and clock mechanism operated by a small lever, the counterpart of the familiar telegraph call box. When the starting lever is depressed a contact is made in the control station causing the magnets in the compensator to close the throw-over switch in the starting position. After a definite time the control station automatically causes this contact to open and makes another contact which causes the magnets in the compensator to transfer the throw-over switch to the running position. The time element is introduced by the clock mechanism in the control station and is adjustable. When desired, an inching feature may be included. The advantage of the time element principle as compared with the current-

limit principle lies in the fact that, with a time element starter the autotransformer is in circuit only a given length of time. With a current-limit device a heavy load may prevent the transfer from starting to running position. The autotrans-

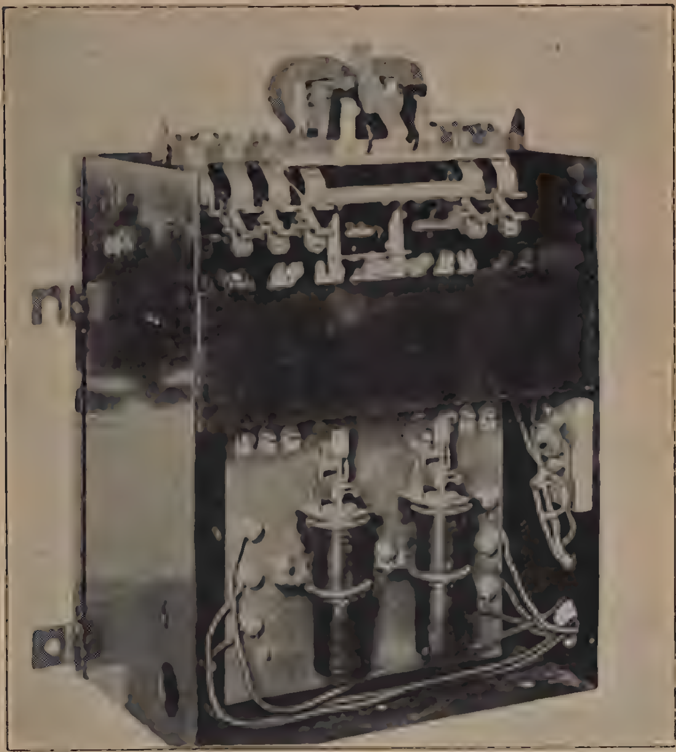


FIG. 226.—Automatic compensator for squirrel-cage induction motor.

former then remains in circuit, heavily loaded, and is likely to suffer damage.

The compensator above described is equipped with overload relays which are in circuit for the running position. The motor is thus protected against too severe conditions at the time of transfer or during normal running. The equipment may be arranged for either no-voltage release or no-voltage protection. As many control stations may be used as desired. The diagram

of connections, Fig. 227, shows three stations, one having an "inching" feature and one being a "stop" station only. No-voltage protection is provided. When the starting lever is depressed a control circuit is completed from C_3, through overload relays and "stop" contacts to C_1 thence through "start" contact to C_4. This energizes the magnet closing the starting contacts in the compensator. After an interval this control circuit is broken. At the same time a circuit is made momentarily from C_1 to C_2, energizing the magnet closing the running

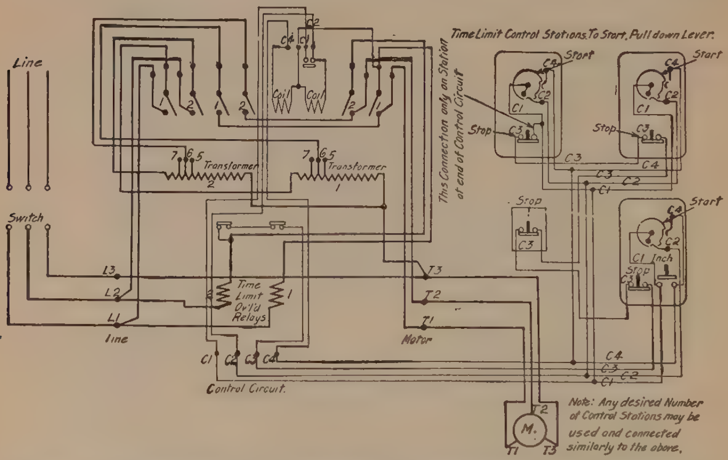


FIG. 227.—Connections for automatic compensator for squirrel-cage induction motor.

contacts in the compensator. A holding circuit from C_1 to C_2 is then completed by means of an auxiliary contact in the compensator. The compensator now remains in running position unless an overload relay or stop button opens the circuit between C_3 and C_1 or unless the voltage fails.

Reverse Switches.—The equipments described above are primarily in the nature of starters for squirrel-cage motors having a continuous running duty and single direction operation. A switch may be supplied for reversing the primary leads of a polyphase motor, this switch being employed separately but in conjunction with some form of starting device or compensator. Such an arrangement may not be entirely safe and should be

considered only as an emergency measure or in case where reverse operation is very infrequent. Where frequent reversing is to be expected some type of control providing a suitable means for reversing the primary leads is necessary. Drum controllers have been developed for this service. The majority of these drums are for use with small motors or motors having high resistance rotors and suitable for starting by direct connection to the lines. Figure 228 gives a connection diagram for such an installation.

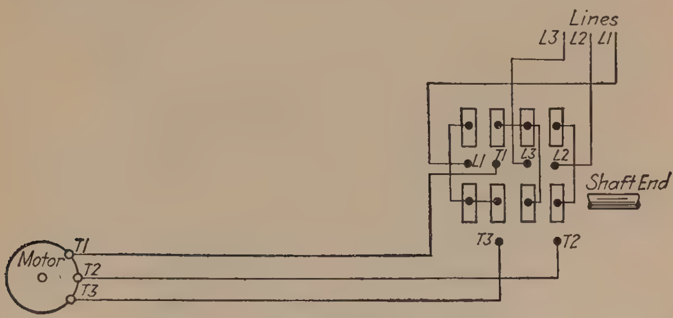


FIG. 228.—Drum type reversing switch and starter for squirrel-cage motor with high-resistance rotor.

WOUND-ROTOR INDUCTION MOTORS

Types of Controllers.—The control of the wound-rotor induction motor involves switching in both primary and secondary circuits. The primary must be connected to or disconnected from the lines. If reversing service is required the primary connections must be reversed. The primary circuit switching may be handled by a circuit-breaker, an oil circuit-breaker or, if of low voltage, by contacts of a drum controller or face plate. The secondary circuits may be handled by a separate device such as a rheostat with provision for cutting out resistance. Figure 229 illustrates a face-plate controller provided with contact arms and segments for reversing the primary connections and having also three sets of segments and three secondary contact arms connected to cut out resistance in the three phases of the secondary circuit. The connections are shown in Fig. 230. Multiple-switch controllers may be employed to cut out

secondary resistance. Figure 231 illustrates such a device for use with an induction motor and Fig. 232 shows the connections. Drum controllers are also frequently used. The connections for a drum controller for varying the secondary resistance of a

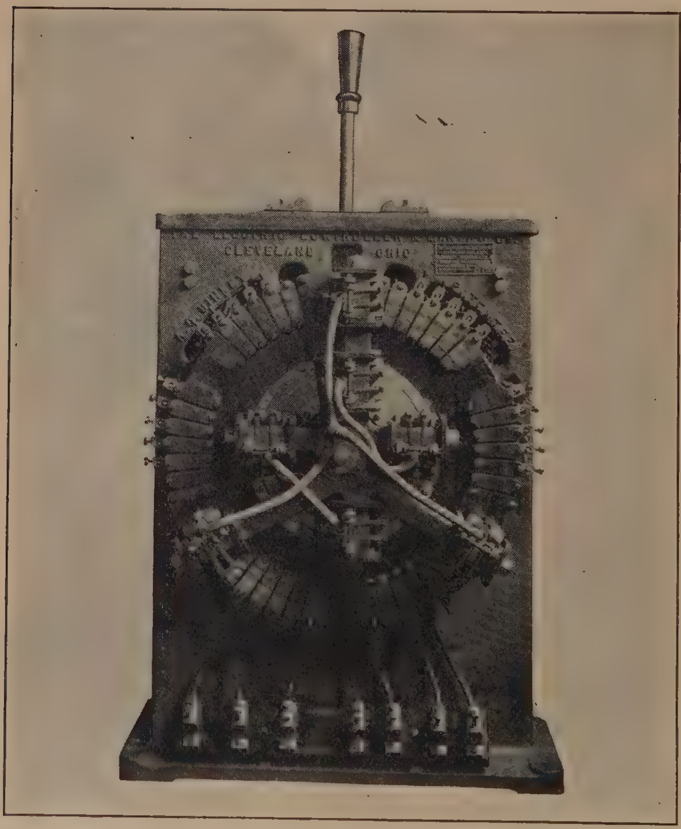


Fig. 229.—Face-plate type controller for wound-rotor induction motor.

wound-rotor induction motor are shown in Fig. 233. It may be noted that the resistors are not cut out simultaneously and equally in all phases. It is not necessary that this be done. More speed points with fewer contacts and complication are secured by the practice indicated. Figure 234 shows a secondary resistance controller in which three graphite resistor col-

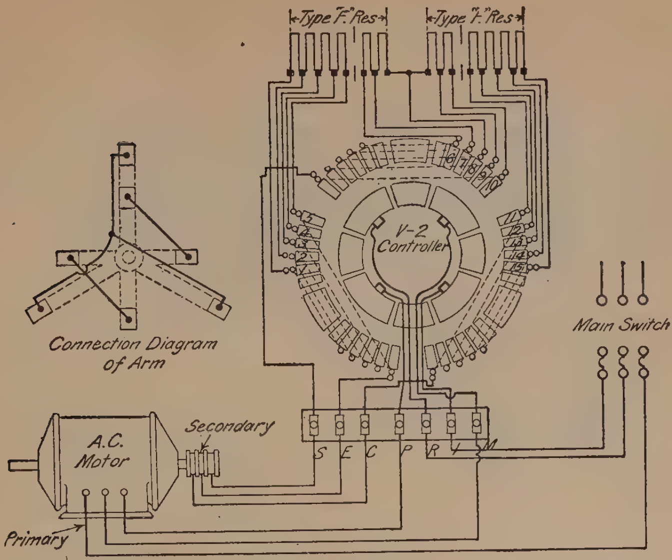


FIG. 230.—Connections for face-plate type controller for wound-rotor induction motor.

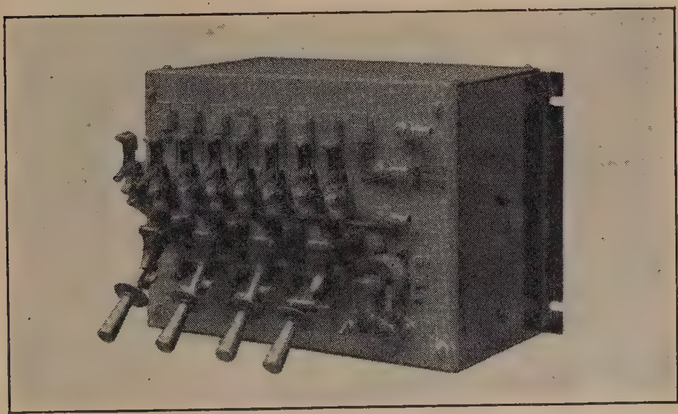


FIG. 231.—Multiple-switch type secondary starter for wound-rotor induction motor.

umns are used, pressure being applied to all three equally by the regulating handle.

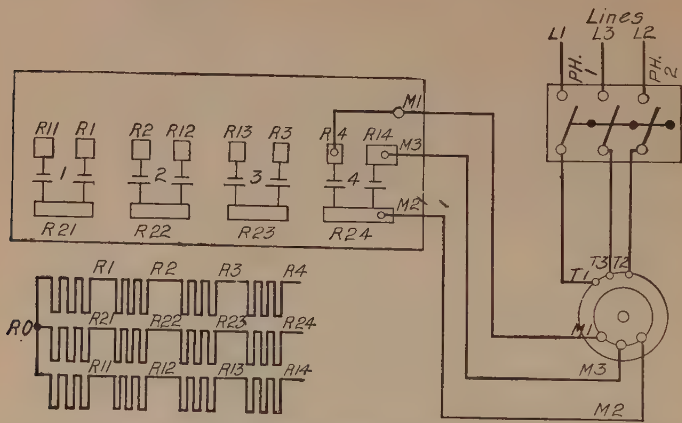


FIG. 232.—Connections for multiple-switch type secondary starter for wound-rotor induction motor.

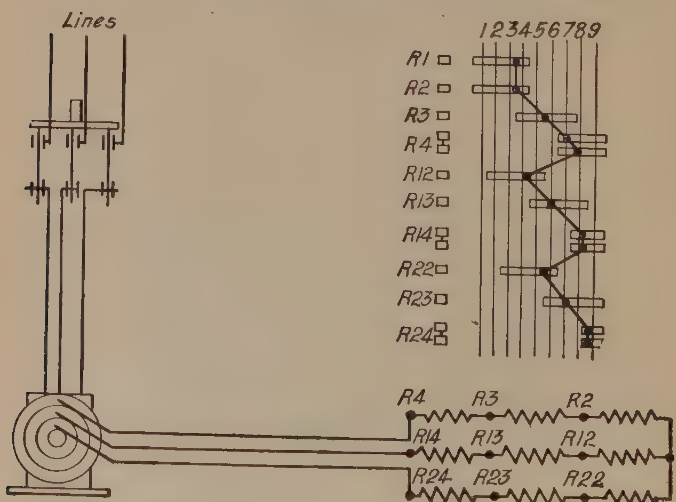


FIG. 233.—Connections for secondary drum type starter for wound-rotor induction motor.

Interlock Requirements.—A wound-rotor induction motor should be started with its secondary resistance in circuit, the resistance being cut out as the motor is accelerated. Where

separate devices are used for controlling the primary and secondary circuits, some form of interlock, mechanical or electrical, is desirable.

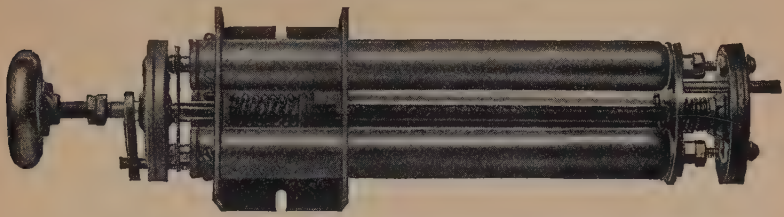


FIG. 234.—Secondary controller for wound-rotor induction motor, using graphite column resistor.

Drum Controllers.—Separate devices for control of primary and secondary circuits are commonly used where single-direction rotation is desired. When reversing service is required the

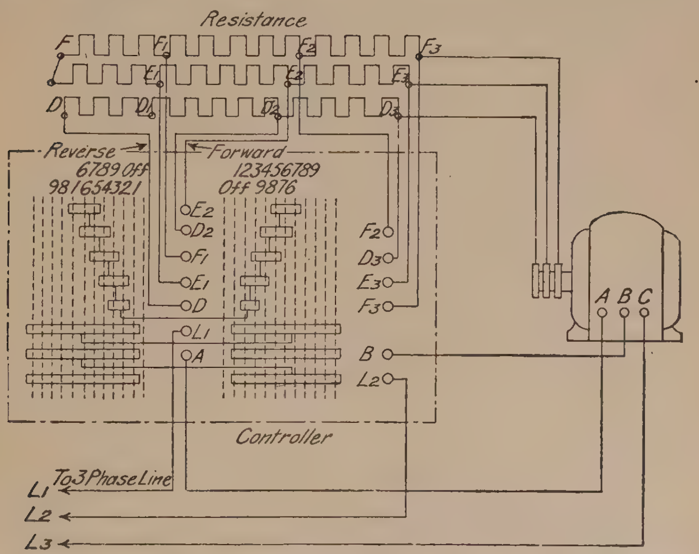


FIG. 235.—Connections for combined primary reversing and secondary control drum for wound-rotor induction motor.

drum controller handling both primary and secondary connections is more frequent. The use of this type of equipment is not confined to reversing service, however, as it is utilized for

single-direction service also. Figure 235 shows the connections for a drum controller handling both primary and secondary circuits of a wound-rotor type induction motor. The primary connections are located in the lower portion of the drum and are arranged to be submerged in oil to suppress the arcing.

Protection.—Where the primary circuit switching is done by means of circuit-breakers or oil switches, protection for excess current and no voltage may be provided upon these devices. Where drum type controllers handle the primary switching it is necessary to provide separate protective devices.

Secondary Circuit Three-phase.—It is to be noted that the secondary circuits of practically all wound-rotor induction motors are three-phase, even though the primary be two-phase. As the stator and rotor are related through a magnetic medium only, this is possible. It results in simplification in lines of motors and controllers. In some special cases, where auxiliary machines in the secondary circuit are employed, a six-phase secondary connection is used.

CHAPTER XVIII

ALTERNATING-CURRENT MAGNETIC CONTROL ELEMENTS

The A.-C. Contactor.—The alternating-current magnetic controller resembles its direct-current prototype in that it comprises an assembly of contactor and relay units working in combination. In their details, however, direct-current and alternating-current magnetic controllers differ materially.

The alternating-current magnet differs from the direct-current magnet in that it is excited by a pulsating current. This introduces several complications. In order to minimize iron losses in the magnet coils, giving rise to heating, it is necessary that the magnetic circuits be entirely or largely built up of laminations. In a direct-current magnet the coil resistance alone determines the current flow under a given voltage. In the case of an alternating-current magnet reactance plays an important part. The reactance is a function of the magnetic air gap, hence it varies according to the position of the plunger or armature. As the exciting current of a direct-current contactor magnet remains constant, the magnetomotive force is constant. The pull on the armature varies as the square of the air gap; thus, as the contactor closes, the pull increases rapidly, tending to seal the contactor firmly. As an alternating-current contactor closes, its coil reactance increases and the power of the coil decreases. This tends to offset the tendency for the pull to increase as the air gap is lessened. The sealing power of an alternating-current contactor magnet is relatively low. The current through the magnet coil with the contactor closed is only about one-fifth of the flow with the contactor open.

The pull of the magnet of a direct-current contactor is continuous; there is thus no tendency to chatter. An alternating-current contactor energized by a single-phase coil carries a

flux which passes through zero at every reversal of the current. This leads to a tendency to chatter. This tendency is relieved through the use of a U-shaped magnet core giving a minimum air gap with the contactor closed and by the use of "shading coils" which produce a small out-of-phase flux sufficient to retain the contactor closed while the main flux passes through zero. The tendency to chatter can be overcome through

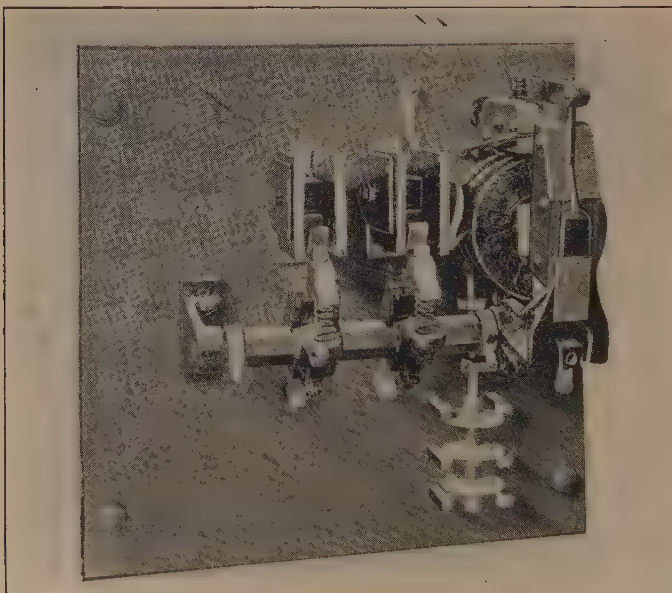


FIG. 236.—Two-pole alternating-current magnetic contactor unit.

use of multi-phase magnet coils on the contactors but the additional complication is undesirable and single-phase coils are commonly used.

Since the control of alternating-current motors involves the simultaneous opening or closing of contacts in the different phases, alternating-current contactors are commonly multipolar. Two-pole contactors are the more common but three- and four-pole contactors are entirely practical. Figure 236 shows a two-pole contactor unit suitable for voltages up to 600 volts. The unit comprises a rather powerful magnet with

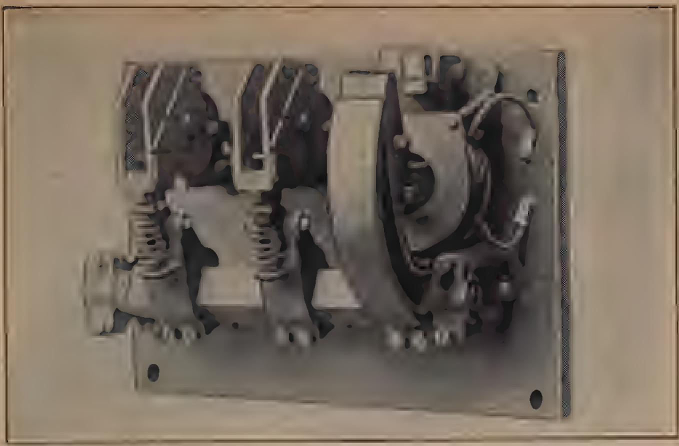


FIG. 237.—Two-pole alternating-current magnetic contactor unit.

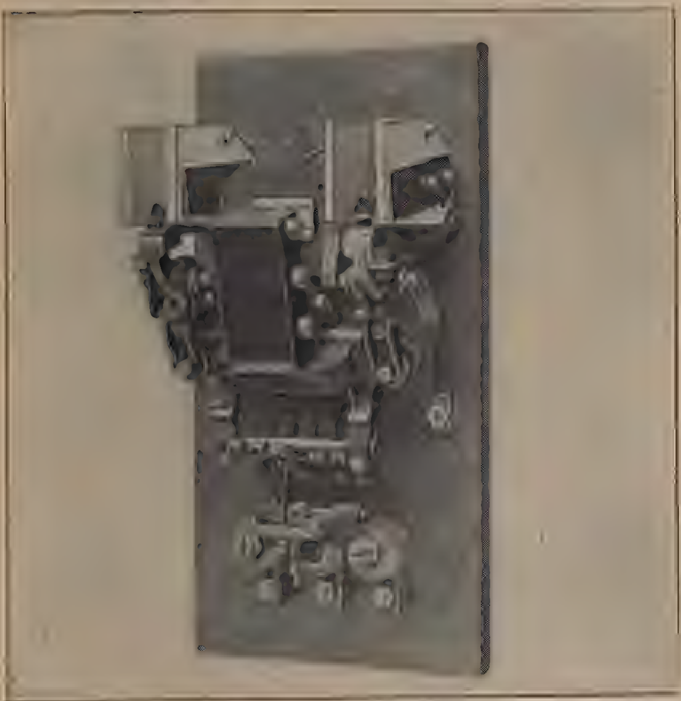


FIG. 238.—Two-pole alternating-current magnetic contactor unit with three-phase accelerating relay.

liberal lever arm and an insulated shaft carrying the two contact units. Figure 237 shows a similar unit by a different manufacturer. Figure 238 shows a third type. In this unit the two contacts are located on either side of the magnet.

Oil-immersed Contactors.—Contactors of the type just described are suitable for use on circuits of low voltage and find extensive use upon magnetic controllers for motors up to 600 volts. For higher voltage control oil-immersed contactors

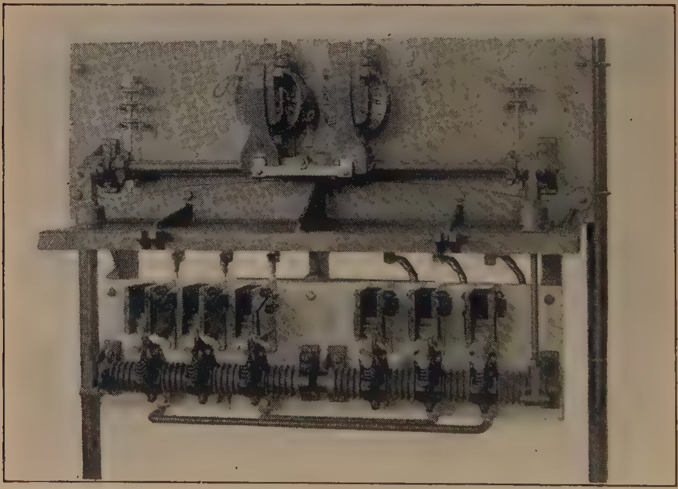


Fig. 239.—Oil-immersed magnetic contactors for high-voltage alternating-current service.

are more commonly employed. Figure 239 shows a three-pole oil-immersed reversing contactor equipment for 2,300-volt duty.

High-voltage Air-break Contactor.—Oil-immersed contactors are suitable and satisfactory for the many applications which involve only occasional starting and stopping. When the service is more frequent, as in mine hoist duty, the oil-immersed contactor is not suitable because of rapid carbonization of the oil. For frequent duty, the high-voltage air-break contactor is best adapted. Figure 240 shows a three-pole contactor unit of this type. The liberal clearances and large arc shields are particularly noticeable.

Rupturing Ability.—It is to be noted that neither oil-immersed nor air-break contactors of the high-voltage type have sufficient rupturing capacity to serve as circuit-breakers. They will handle safely the loads incident to normal operation. To protect against overloads and short circuits it is advisable

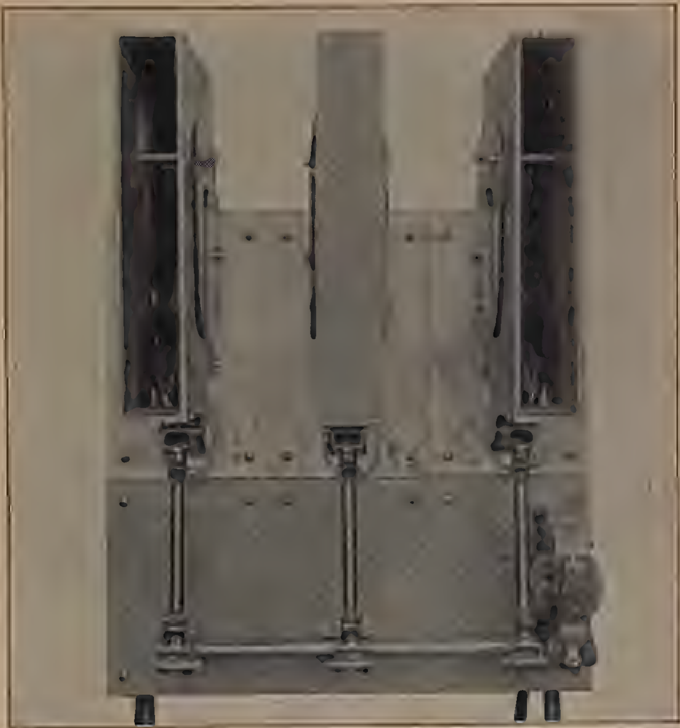


FIG. 240.—Air-break magnetic contactors for high-voltage alternating-current service.

to install, ahead of the magnetic controller, a suitable oil switch, the overload trip devices acting upon the oil switch. On the other hand, low-voltage contactor units are commonly employed in conjunction with overload trip devices.

Voltage Relay.—Relays play an important part in the make-up of alternating-current controllers. The more common types are voltage relays, overload relays and accelerating relays

operating on the time element and current-limit principles. Figure 241 shows a voltage relay which is merely a small shunt-wound single-phase alternating-current contactor of the clapper type. This contactor carries control or pilot circuits only. It is more commonly employed to provide a no-voltage protection feature.

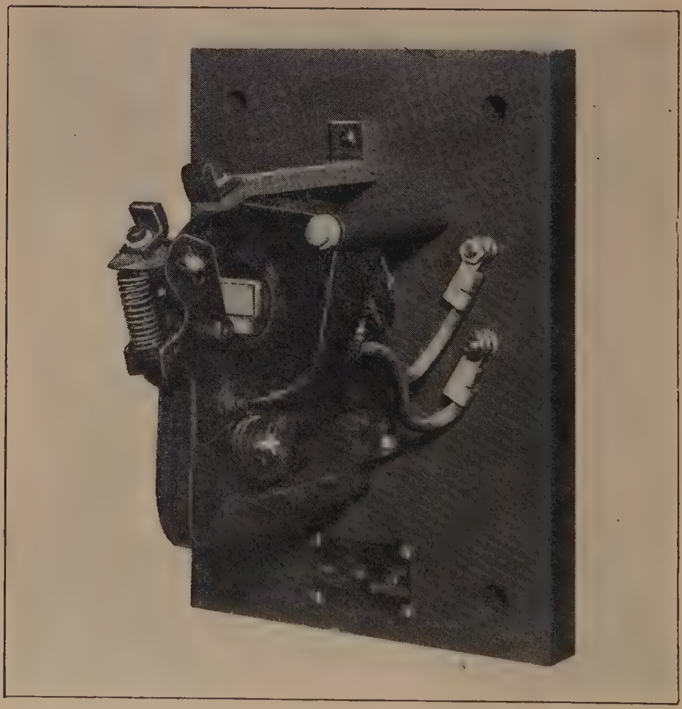


FIG. 241.—Alternating voltage relay.

Overload Protection.—An alternating-current overload relay of the instantaneous trip, magnetic reset type is shown in Fig. 242. An overload relay having an inverse time element trip feature is shown in Fig. 243. The time element is obtained through use of an oil dash pot. The use of time element overload relays is common in connection with the control of induction motors. These relays are adjusted not to trip under the momentary starting inrush but to protect against sus-

tained overloads. It is the common practice to install two overload relays in two of the lines feeding a polyphase induction motor. Protection is thus secured against overloading in any phase. A measure of protection is also afforded against single-phase operation, resulting in overloading one phase. In this connection it may be noted that the primary or line contactor

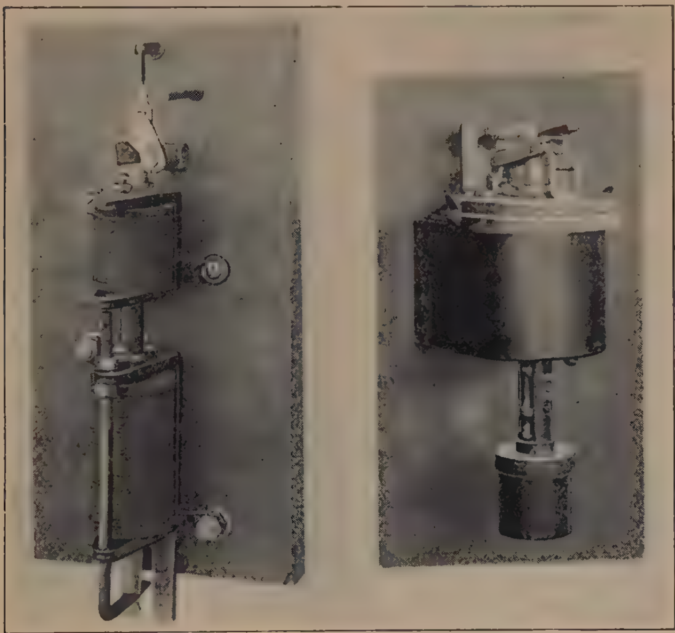


Fig. 242. Fig. 243.

Fig. 242.—Alternating-current, instantaneous trip, magnetic reset overload relay.

Fig. 243.—Alternating current time element trip overload relay.

which is tripped by the overload relays is a multi-pole contactor and opens both phases of a two-phase circuit and either two or three lines in a three-phase circuit, avoiding single-phase operation.

An overload relay of the induction type is shown in Fig. 244. This relay secures its time element through rotation of an aluminum disc between permanent magnets, supplying a retard-

ing force. It has an inverse time characteristic. Its action may be predetermined with greater accuracy than is possible with relays of air or oil dash pot types. The use of this type of relay is largely confined to the larger motors because of its relatively higher cost.

Accelerating Relays.—For the acceleration of induction motors by magnetic controllers, relays of either time element or current-limit types find extensive use. Figure 245 shows a

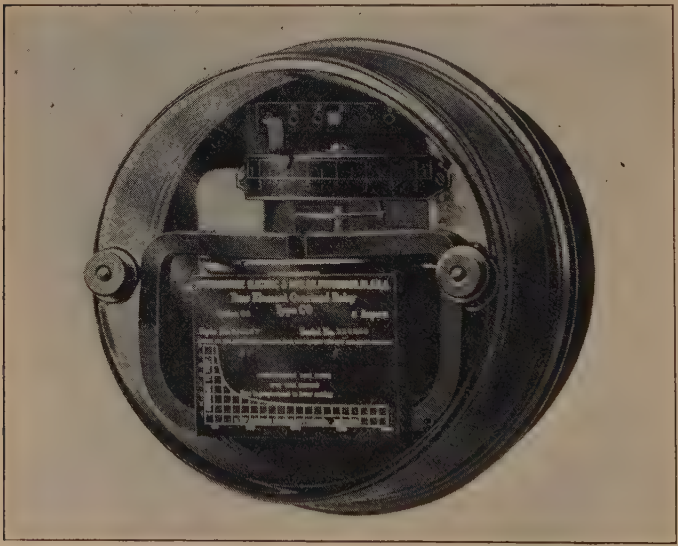


FIG. 244.—Induction type overload relay.

time element accelerating relay for an alternating-current controller. The relay coil is energized ordinarily through a pilot circuit from the master controller. The time element feature is obtained by means of an air dash pot which has a needle valve adjustment.

Accelerating relays of the current-limit type must, of necessity, be connected in the primary circuit of squirrel-cage induction motors. In the case of wound-rotor motors the accelerating relay or relays may be connected in either the primary or the secondary circuit. Figure 246 shows a current-limit relay,

the current coil of which is connected in the primary circuit for the control of either a squirrel-cage or wound-rotor motor. This relay has also a shunt coil which is connected in series with an accelerating contactor. When the shunt coil is energized its armature is attracted. This releases the armature of the current relay, permitting it to drop when the current has fallen to the prescribed value. This relay closes contacts which short-circuit the shunt coil of the relay and thus cause the clos-

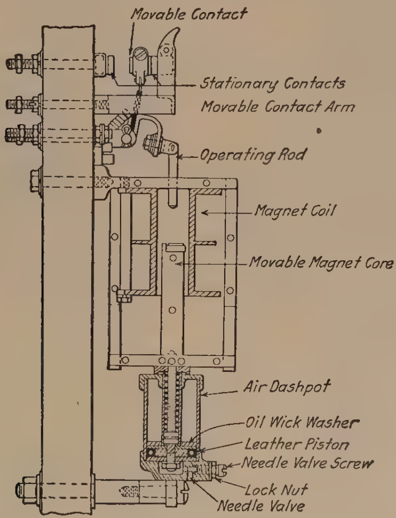


FIG. 245.—Time element accelerating relay

ing coil of the accelerating contactor to be fully energized, closing same.

The relay above described is electrically interlocked with the controller through the medium of the shunt coil. A current-limit relay mechanically interlocked with a contactor is shown in Fig. 238. When the contactor is open the relay cannot close. When the contactor closes, the relay armature is held open by the current in the series coil until that current falls to a prescribed value. The relay armature then drops, closing a control circuit to permit further acceleration of the motor. On a magnetic controller for a squirrel-cage motor the relay coil is connected in the primary circuit. On a con-

troller for a wound-rotor motor the relay coil is connected in the secondary circuit. This arrangement has the advantage of simpler connections. It has some advantage in that motors of differing primary voltages usually have identical secondaries, so that a lesser variety of relay coils covers a wide range of motors. It is to be noted that the frequency in the secondary

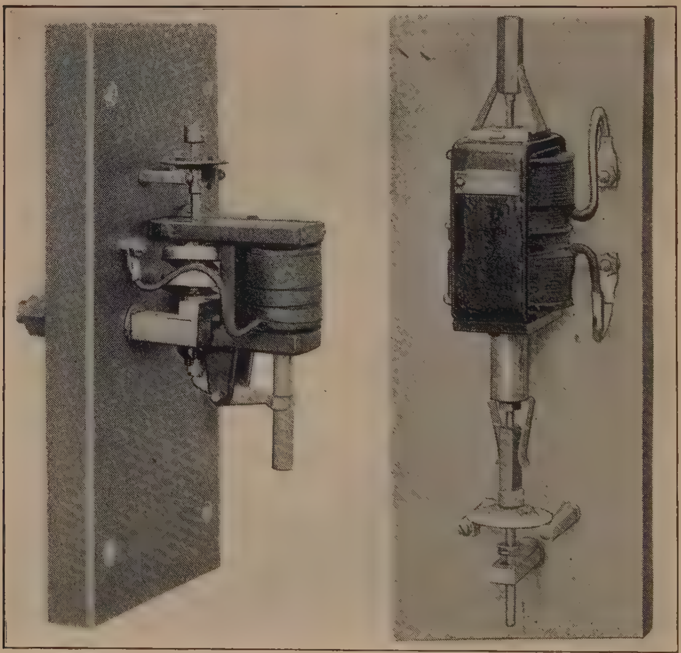


FIG. 246. FIG. 247.

FIG. 246.—Primary current limit accelerating relay.
FIG. 247.—Notch-back or jam relay.

circuit of a wound-rotor motor varies and becomes low as the motor approaches synchronism. A single phase relay of this type requires careful design to avoid chattering as the current passes through zero at low frequencies.

To avoid the last-named difficulty a three-phase current-limit relay, connected in the secondary circuit, is employed by one manufacturer. This is shown mechanically interlocked with

a contactor in Fig. 238. The three coils are connected in the three secondary lines, usually forming the Y. As the currents in the three coils are out of phase, the pull of this relay is constant. It therefore has no tendency to chatter and permits of relatively accurate calibration.

Jam Relay.—The relay shown in Fig. 247 is a notch-back or jamming relay. It carries a series coil which is connected in the secondary circuit of a wound-rotor motor. Its function is to open a circuit when the current exceeds a set value, causing resistance to be cut into the secondary circuit of the motor. This relay has separate adjustments to determine the current values at which it will pick up and drop, respectively closing and opening the control circuit governed.

CHAPTER XIX

ALTERNATING-CURRENT MAGNETIC CONTROLLERS

It will be the purpose of this chapter to illustrate and discuss some of the more common and simple magnetic controllers for use with polyphase induction motors. Controllers for squirrel-cage motors will be considered first, those for wound-rotor motors following.

PRIMARY RESISTANCE STARTER

Composition.—Magnetic starters of the primary resistance type are quite commonly used, particularly with the smaller motors. A starter of this type is illustrated in Fig. 248, the connections being given in Fig. 249. The starter comprises a main line switch and a control circuit switch, a main line contactor, a time element accelerating relay, a three-pole accelerating contactor and two overload relays of the time element trip, instantaneous reset type. The operation is as follows:

Operation.—When the "start" button is depressed, the pilot circuit through the closing coil of contactor 1 is completed. Closure of that contactor connects the motor primary winding to the line with resistors in series in all phases. An auxiliary contact on contactor 1 causes this unit to remain closed after the start button is released. Simultaneously with the closure of contactor 1 the accelerating relay coil is energized. Closure of the relay contacts is delayed by a dash pot on this contactor-type relay. After the prescribed time, these contacts close. The closing coil of accelerating contactor 2 is then energized. Closure of this contactor short-circuits the primary accelerating resistors. No-voltage protection is secured in that failure of voltage will cause all contactors to open. The line contactor will not then close until the "start" button is depressed.

Momentary opening of an overload relay or pressing the "stop" button has a like effect.

Performance.—Magnetic starters of the primary resistance type are frequently provided with resistors in but two legs of the circuit. They are simpler to that extent. However, an

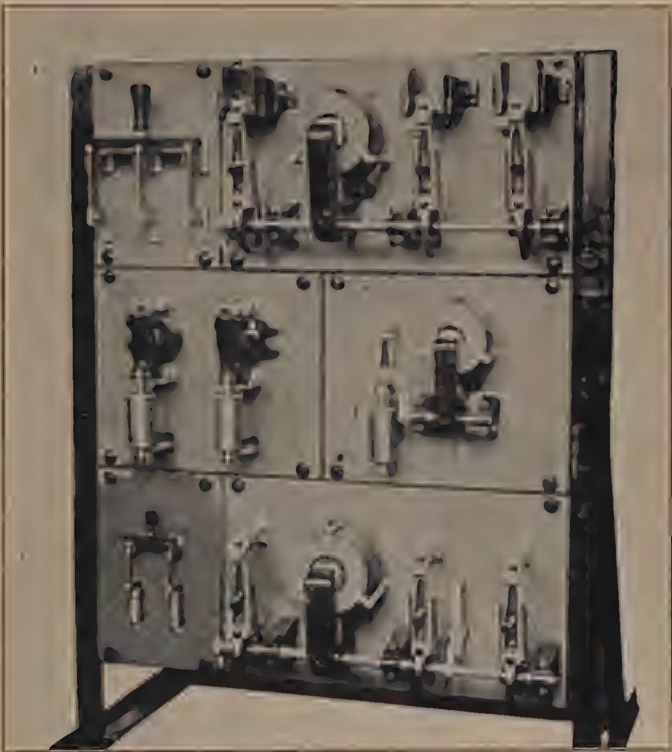


FIG. 248.—Primary resistance starter for squirrel-cage induction motor.

unbalanced voltage is impressed upon the motor phases with this scheme. The motor attempts to balance the phase voltages and may circulate rather high local current in so doing. Except for occasional starting of small motors the use of resistors in all three phases is considered, by the writer, as preferable.

Primary resistance starters need have ordinarily but one

accelerating step. The initial current inrush causes relatively high drop in the resistors, causing rather low voltage to be impressed upon the motor. As the motor current falls off,

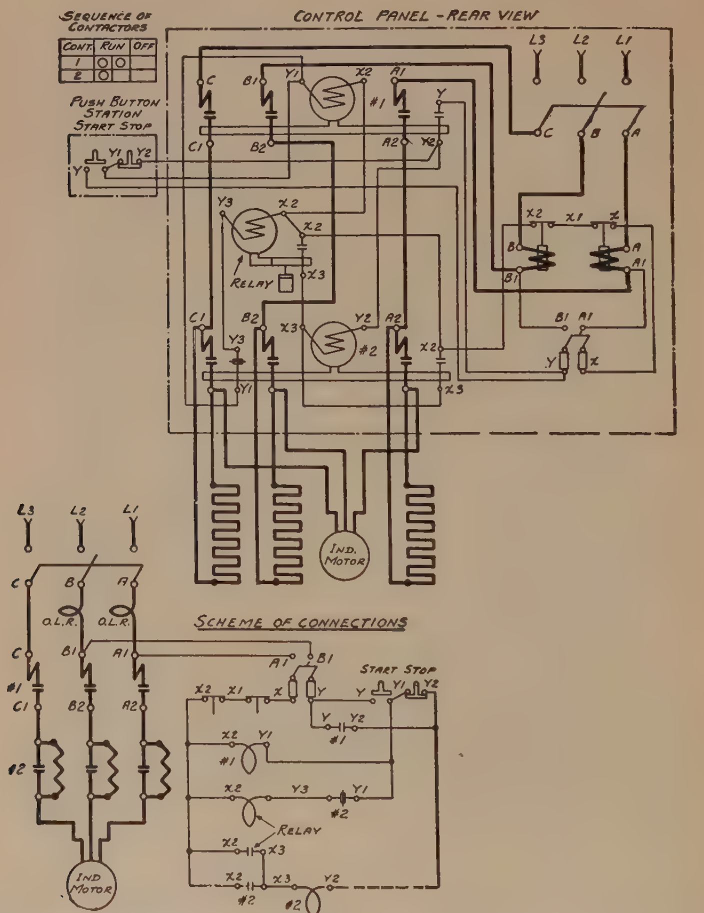


Fig. 249.—Connections for primary resistance starter for squirrel-cage induction motor.

the resistance drop decreases, automatically increasing the voltage impressed upon the motor. The ordinary squirrel-cage motor has its lowest torque per ampere at standstill, the torque increasing as the motor accelerates. A value of resist-

ance which will pass sufficient current to start the motor will easily accelerate it. A possible exception is in the case of a load which increases rapidly with the speed.

It is to be noted that, the heavier the load to be started, the greater is the resistance drop and the lower the voltage impressed upon the motor during acceleration. It is necessary, where starting conditions may be severe, to reduce the resistance to a value which will permit the required starting torque for the maximum condition. The primary resistance type of starter has advantage in simplicity, low first cost, relative ease and low cost of repair and provides continuous acceleration without a throw-over interruption. It has the disadvantage of limited torques, higher starting current peaks and lesser economy. These disadvantages are often nominal. The primary resistance starter has much to recommend its use, particularly for the smaller motors.

TRANSFORMER TYPE STARTERS

Starter with Transfer Relay.—Magnetic contactor panels, based on the auto-starter principle, are in common use. A panel of this type is illustrated in Fig. 250. The connections are shown in Fig. 251. The panel comprises a two-pole line contactor and a four-pole starting contactor, mechanically interlocked. A current-limit accelerating relay is interlocked with the starting contactor. A transfer relay is used to govern the throw-over operation. No-voltage protection is obtained through use of a voltage relay. An autotransformer of the air-cooled type is supported at the rear of the panel. This transformer is supplied with taps for adjusting the starting voltage. The panel illustrated carries fuses for overload protection. In the diagram overload relays are indicated. The action of the control is as follows:

Operation.—When the "start" button is depressed, the voltage relay coil is energized, closing this relay. An auxiliary contact on this relay causes it to remain closed after the "start" button is released. Closure of the voltage relay causes the closing coil of the four-pole starting contactor to be energized, the pilot circuit passing through the transfer relay. When the

four-pole starting contactor closes, the motor is connected to the low-voltage taps of the autotransformer. The series coil of the accelerating relay is now in circuit in one motor lead. When the four-pole contactor closes, the accelerating relay is

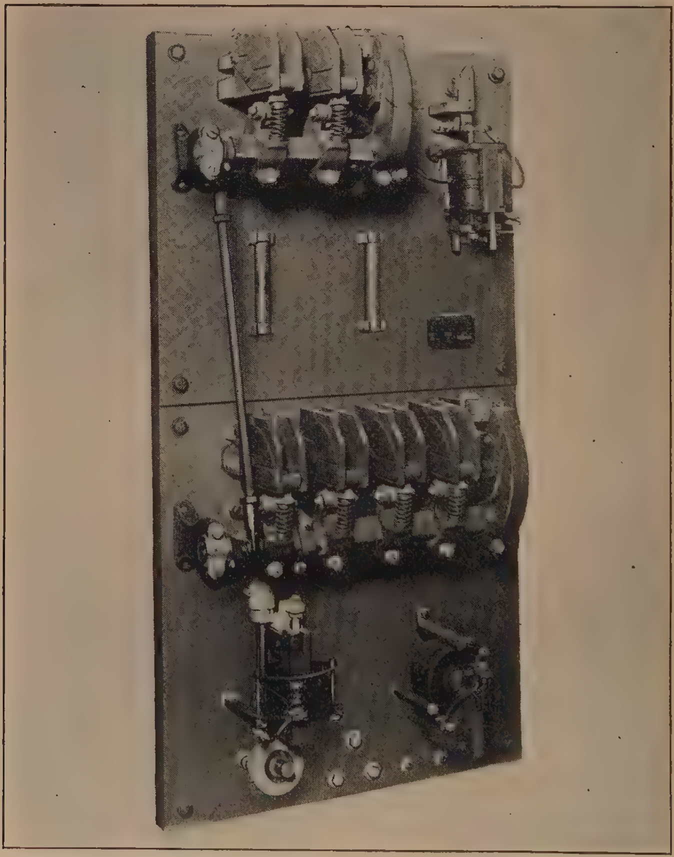


FIG. 250.—Autotransformer type magnetic starter for squirrel-cage motor, with transfer relay.

released and is mechanically free to drop. It is held up, however, by the starting current peak through the series coil. When this current is sufficiently reduced the relay drops. This closes a pilot circuit through the transfer relay coil. When

the transfer relay is energized its plunger is raised. This causes the contact at 1 to open and that at 2 to close. The

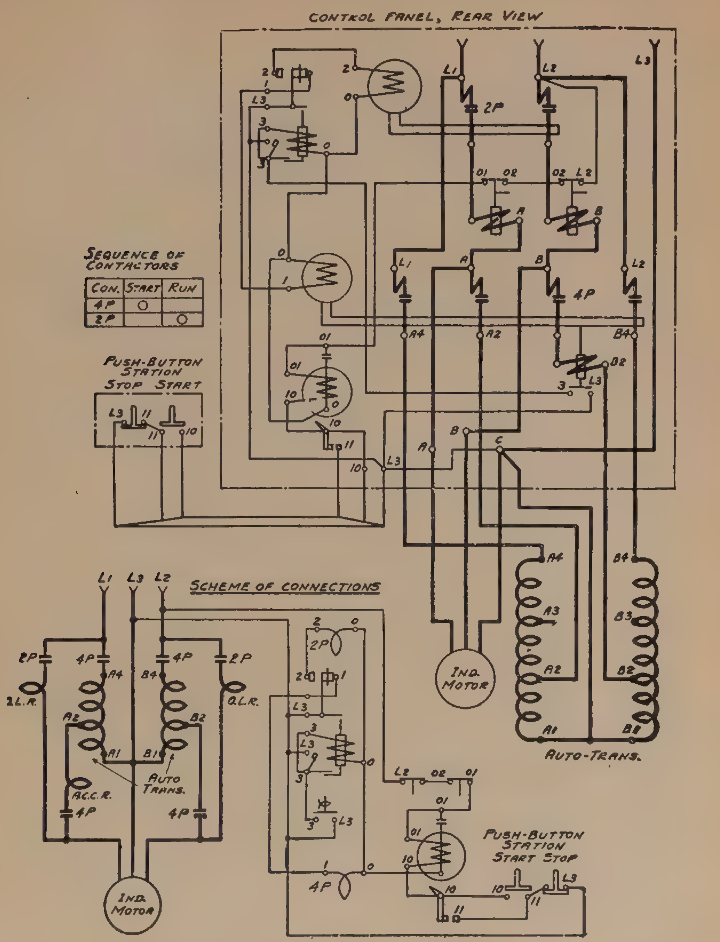


FIG. 251.—Connections for autotransformer type magnetic starter for squirrel-cage motor, with transfer relay.

auxiliary contact at L_3 also closes, completing a holding circuit to retain the transfer relay in the new position.

The opening of transfer relay contact 1 interrupts the circuit of the closing coil of the four-pole starting contactor,

causing this unit to open. The closure of transfer relay contact 2 establishes a pilot circuit through the closing coil of the two-pole line contactor, causing it to close. This connects the motor directly to the line, bringing the overload relays into circuit also.

Opening of the voltage relay interrupts the pilot circuit of the transfer relay coil, allowing the latter to open and remain open. When the transfer relay opens, it causes the line contactor to open, so that the motor will not start except in the regular cycle. Opening of either overload relay or depressing the "stop" button opens the circuit of the voltage relay, causing it to open the transfer relay and line contactor in turn.

Starter with Combination Relay.—Another magnetic starter using autotransformers is illustrated in Fig. 252, the connections being given in Fig. 253. The general make-up of this panel is similar to that described above with the exceptions that a voltage relay is not used, a single relay combines the functions of current limit and transfer and a three-phase autotransformer is supplied. This control functions as follows:

Operation.—When the "start" button is depressed, a pilot circuit is closed through the closing coil of starting contactor 1. This pilot circuit passes through a contact of the current-limit transfer relay. Closure of contactor 1 connects the autotransformer in circuit and starts the motor at reduced voltage. An auxiliary contact on contactor 1 serves to maintain the circuit of the closing coil after the "start" button is released, retaining the contactor closed.

When contactor 1 closes, both the series and the shunt coil of the current-limit relay are energized. The shunt coil lifts its plunger, releasing the plunger of the series coil. The latter drops when the current has fallen to the set value. When this plunger drops, the pilot circuit 4–6 is broken and 4–5 is established. This interrupts the pilot circuit of contactor 1, causing it to open. The pilot circuit for line contactor 2 is completed so that it closes, connecting the motor across line voltage. It may be noted that the pilot circuit for contactor 2 passes through an interlock 7–1 on contactor 1, so that the former cannot close until the latter has opened. The small coil 1–5 on the relay is connected in multiple with the closing coil of

contactor 2. This coil holds the current-limit transfer relay in its second position so long as the motor continues to run.

Upon failure of voltage, coils 2 and 1–5 are de-energized.

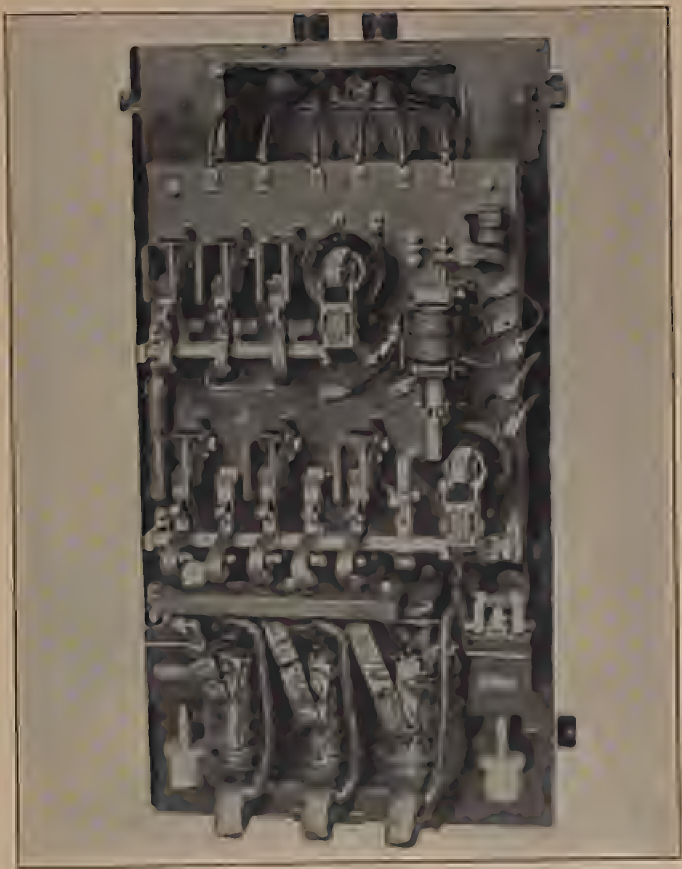


FIG. 252.—Autotransformer type magnetic starter for squirrel-cage motor, with combination relay.

The contactors all open and a start must be made in the regular cycle. Depressing the "stop" button or opening of an overload relay opens the pilot circuit of coils 2 and 1–5, causing them to open and necessitating a new start.

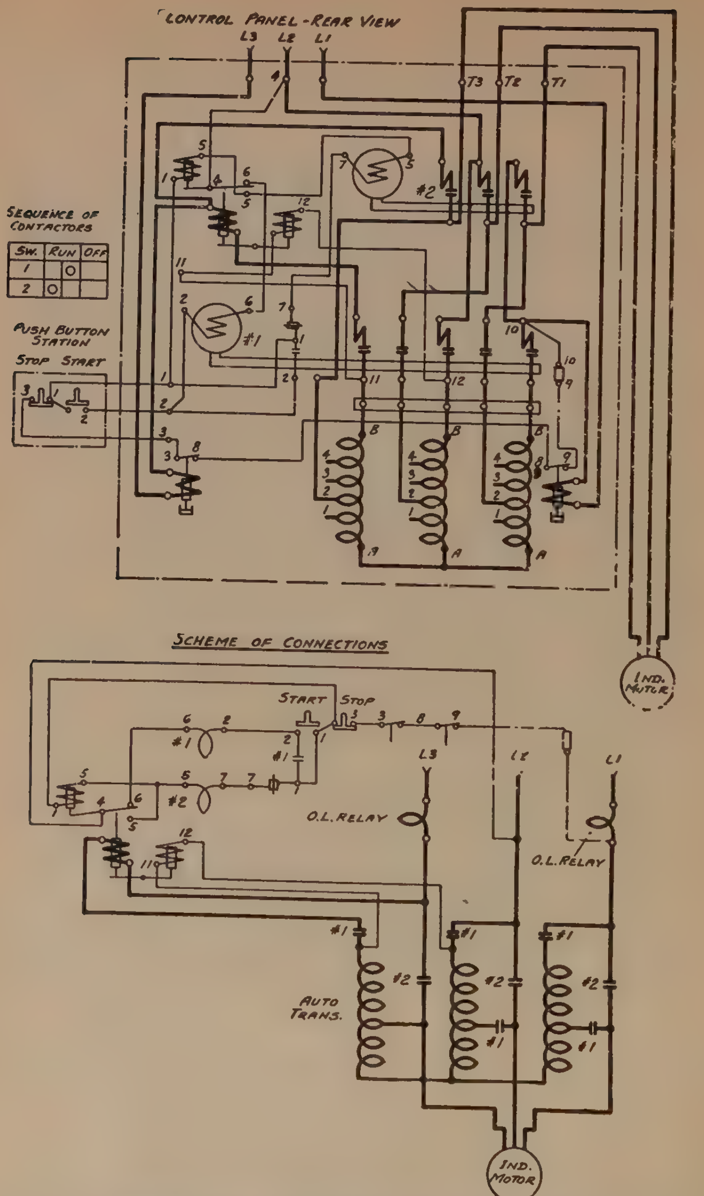


FIG. 253.—Connections of autotransformer type magnetic starter for squirrel-cage motor, with combination relay.

Advantages.—The autotransformer type of magnetic starter for squirrel-cage induction motors has the advantage of providing definite starting voltages, selective through use of taps, the starting voltages being independent of the load. It has the further advantage that the line current is reduced below motor current in the ratio of transformation. This reduces the starting peaks and disturbances and maintains economy. The current-limit principle of acceleration protects the motor

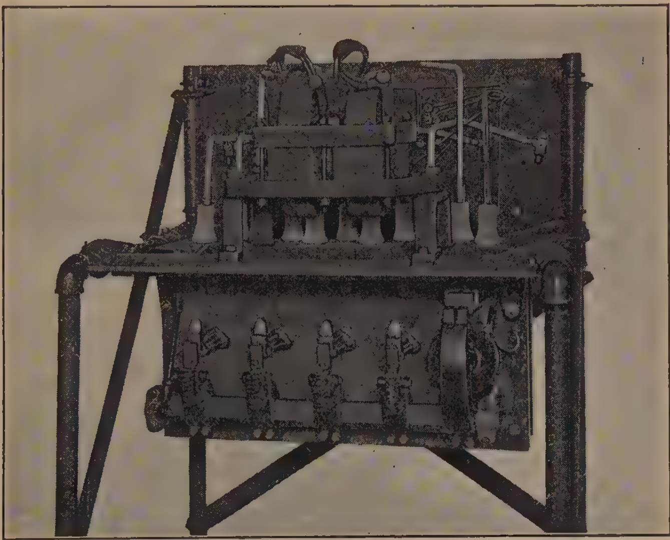


FIG. 254.—Magnetic starter for high-voltage squirrel-cage motor—oil tank removed.

but exposes the autotransformer to damage. If the current in starting does not fall sufficiently to permit this relay to function, the starting connections are maintained and a transformer burnout is likely.

High-voltage Equipment.—The controllers described above are suitable for use with motors of low primary voltage. For use on circuits above 600 volts, magnetic starters are supplied which function along similar lines. The main contactors, however, are arranged to be submerged in oil to assist in suppressing the arcs. An equipment of this type is shown in

Fig. 254. This type of equipment is well suited for the ordinary installation involving but a few operations per day. Where very frequent starting is involved it is necessary to supply high-voltage air-break contactors in place of the oil-immersed contactors. In either case it is proper to install an oil switch ahead of the control panel and to arrange the overload protection to act in conjunction with this oil switch. This is necessary because neither the oil-immersed nor the air-break contactors are suitable to care for high-voltage short-circuit conditions.

CONTROL FOR WOUND-ROTOR MOTORS

Semi-magnetic Controllers.—The control of a wound-rotor induction motor involves switching in both primary and secondary circuits. The control may be full magnetic, involving contactors handling primary and secondary current. Not infrequently manual control, usually an oil switch, is supplied to handle the primary circuit, magnetic contactors being provided for the secondary. On the other hand, magnetic primary control is sometimes provided in conjunction with manual secondary control. A diagram for an equipment of this type is shown in Fig. 255. A main line knife switch, overload relays and voltage relay are supplied on the primary panel. There are also two-pole primary contactors for interrupting or reversing the primary circuit. The drum carries pilot circuit segments and fingers which control the primary contactors and the voltage relay reset. The drum handles the motor secondary circuits, cutting out resistance in steps in the three phases in sequence.

Full Magnetic Controller with Primary Current Accelerating Relays.—A simple non-reversing full magnetic controller is shown in Fig. 256. The connections are given in Fig. 257. The control as shown comprises a three-pole primary contactor, two two-pole secondary contactors, two primary current-limit accelerating relays, two overload relays and the necessary resistors. The action may be outlined briefly.

Operation.—When the "start" button is depressed, the coil of primary contactor 1 is energized, causing that contactor to

SEQUENCE OF SWITCHING

		FORWARD												OFF	REVERSE											
STEP		12	11	10	9	8	7	6	5	4	3	2	1		1	2	3	4	5	6	7	8	9	10	11	12
Sw	FOR.	O	O	O	O	O	O	O	O	O	O	O	O													
	REV.														O	O	O	O	O	O	O	O	O	O	O	O
SECONDARY CONTACTS	2	O	O	O	O	O	O	O	O	O	O	O				O	O	O								
	3								O	O	O						O	O	O							
	4							O	O	O								O	O	O						
	5						O	O	O										O	O	O					
	6					O	O	O												O	O	O				
	7				O	O	O														O	O	O			
	8			O	O	O																O	O	O		
	9		O	O	O																		O	O	O	
	10	O	O	O																				O	O	O
	11	O	O																						O	O
	12	O																								O

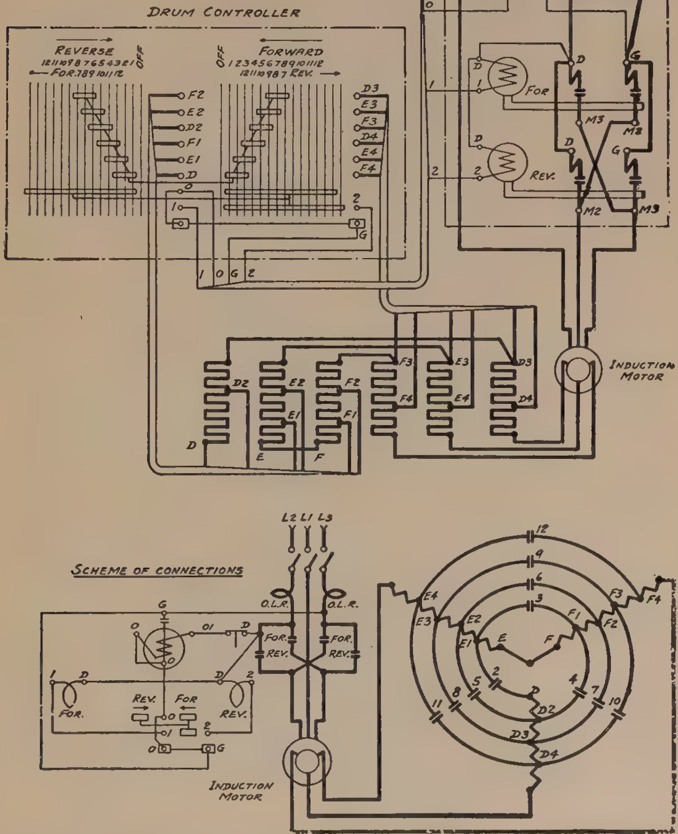


FIG. 255.—Connections for magnetic primary and drum secondary control combination for wound-rotor motor.

close, connecting the motor primary winding across full line voltage. The motor secondary circuit is permanently con-

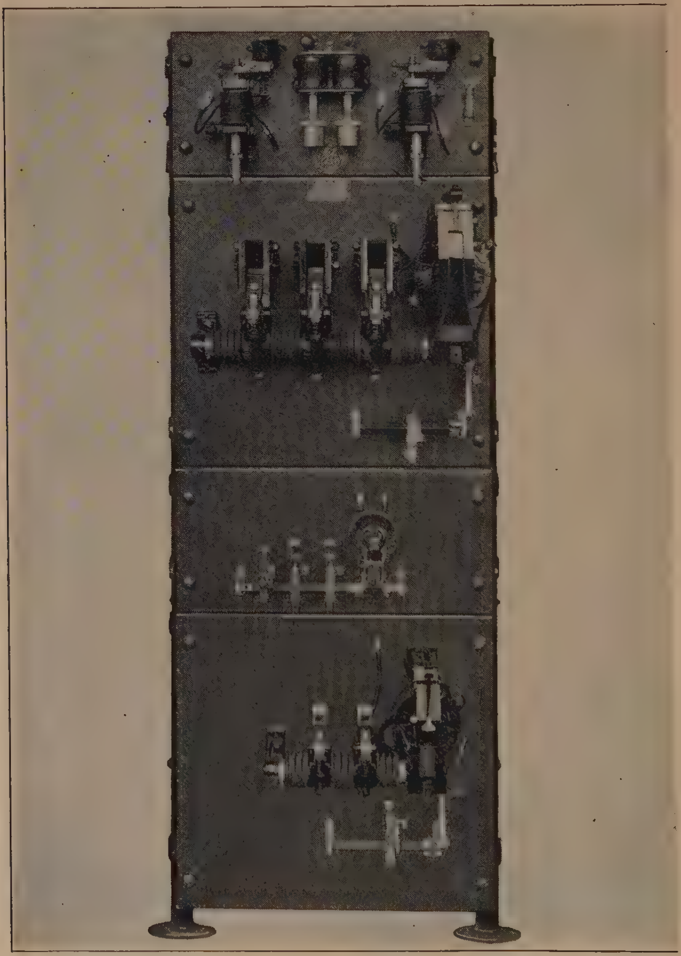


FIG. 256.—Full magnetic controller for wound-rotor motor, using primary current limit relays.

nected to the accelerating resistors. On the first step all the resistors are in circuit. The amount of current flow and torque produced on this point depend upon the resistor values.

When contactor 1 closes, its auxiliary contact completes a holding circuit which passes through the main contacts of this contactor.

When contactor 1 closes, its main contact completes a pilot circuit which includes an interlock on contactor 12 and coil 5–10 of one transfer relay. As the reactance of this coil is

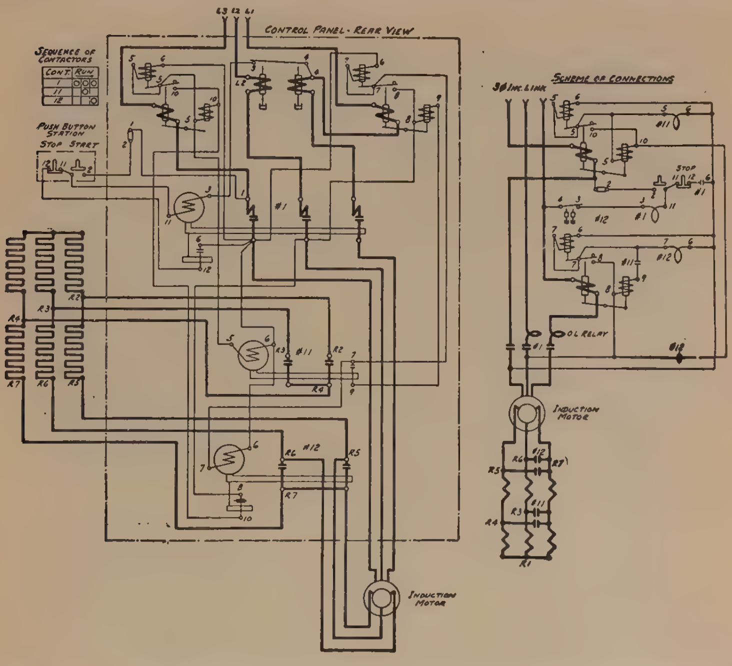


FIG. 257.—Connections for full magnetic controller for wound-rotor motor, using primary current limit relays.

high, most of the voltage in this circuit occurs across this coil, there being insufficient voltage across the closing coil to close contactor 11. Coil 5–10, being energized, lifts its plunger. This permits the plunger in the current coil of this relay to drop so soon as the current through it falls to a sufficiently low value, short-circuiting coil 5–10. This relay is usually adjusted to close at about full-load primary current.

When contactor 11 closes, its auxiliary contact brings into play the other current-limit accelerating relay which functions

in like manner to close contactor 12 so soon as the current in the series coil of the relay drops to the set value. When contactor 12 closes, the current and torque again increase but fall off shortly to a value determined by the load demand.

The controller described above is a comparatively simple equipment of its type, illustrating essentials. A similar control

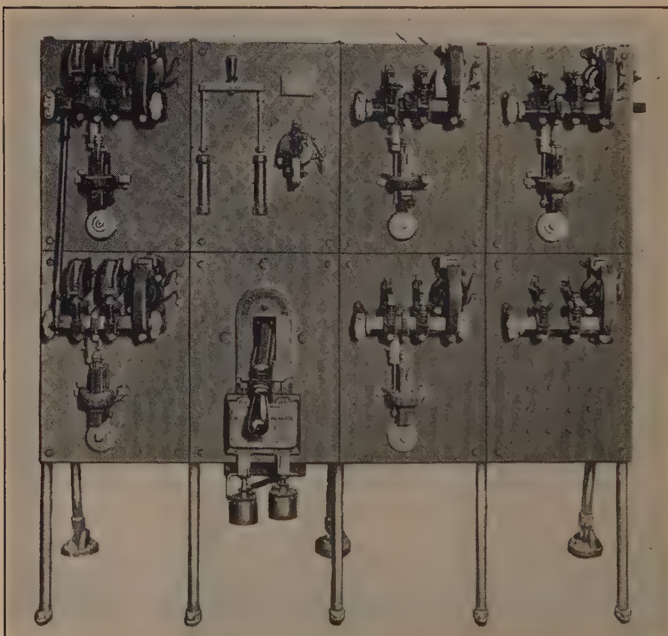


Fig. 258.—Reversing controller for wound-rotor motor, using single-phase secondary current limit relays.

may be supplied having primary reversing contactors, a larger number of accelerating steps, etc. These are variations in application, not in principle.

It is to be noted that the current-limit relays of the above-described controller are electrically interlocked and are governed by the series coils carrying primary current. The primary current and secondary current of a wound-rotor induction motor are approximately proportional, the primary winding

carrying an additional magnetizing current. It is therefore possible to actuate the current-limit relays by secondary current as well as by primary current.

Magnetic Controller with Single-phase Secondary Current Relays.—The controller shown in Fig. 258 is a reversing type magnetic control for a wound-rotor induction motor, with current-limit acceleration governed by secondary circuit single-

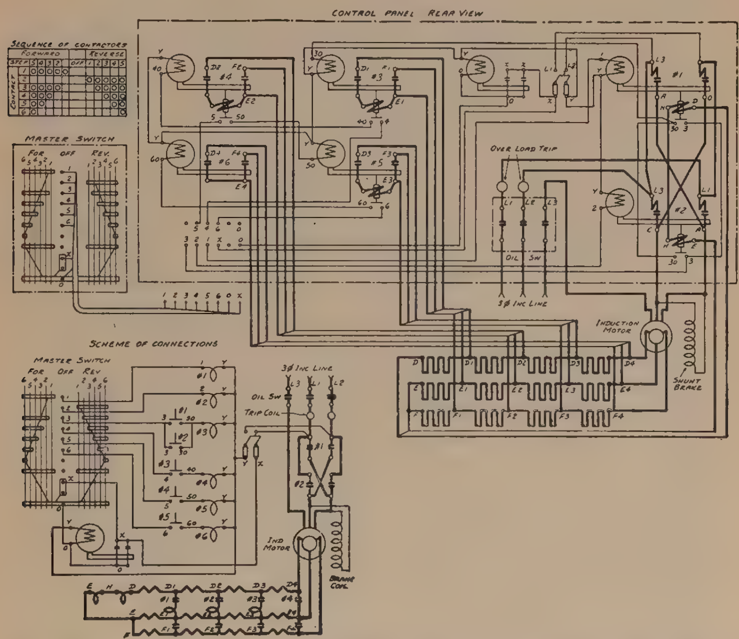


FIG. 259.—Connections for reversing controller for wound-rotor motor, using single-phase secondary current limit relays.

phase relays. The connections of this control are shown in Fig. 259. A primary oil circuit-breaker is provided ahead of the primary contactors, the overload relays acting upon this oil switch. The two-pole reversing contactor units are mechanically interlocked. There are four secondary accelerating contactors, all two-pole units. A pilot circuit switch, voltage relay, drum type master and resistors complete the equipment.

Operation.—On the "off" position of the master the circuit

of the voltage relay is made, closing that relay, which will then remain closed unless voltage fails. Reversing contactors are governed by segments 1 and 2 of the master, according to rotation desired. These contactors accomplish reversal of a primary phase.

When the primary contactors close, the motor starts with full accelerating resistance in circuit. The series relays, mechanically released by the reversing contactors, are connected in the Y of the secondary circuit. The initial inrush of current retains the released relay up until the current falls to the value for which the relay is adjusted. When this relay closes it energizes the coil of the first accelerating contactor 3, providing the master is thrown at or beyond second point so that segment 3 is energized.

In like manner accelerating contactors 4, 5, 6 close in sequence, each governed by the series relay in the secondary circuit as introduced by the previous accelerating contactor and governed also by successive points and segments on the master. Closure of these accelerating contactors accelerates the motor until it finally operates at full speed with the accelerating resistors short-circuited.

The amount of secondary resistance supplied with this controller may be sufficient to limit the motor current even though the motor be plugged. The torque developed by the motor with this high secondary resistance may be insufficient to start a heavy load. Under such a condition the current-limit relays would not permit reduction of the secondary resistance. A so-called "maximum torque button," not shown, is then supplied to by-pass the series relays and close accelerating contactor 3, thus reducing the secondary resistance to such a value that the motor will develop approximately its maximum torque.

Magnetic Controller with Three-phase Secondary Current Relays.—Current-limit acceleration is obtained in the above controller through use of series relays in the secondary circuit. This arrangement has merit in affording simplicity in wiring. It is also of advantage to the manufacturer in that the secondary circuits of a line of motors are usually identical, although the primaries may be wound for different voltages. On the other hand, the frequency in the secondary circuit is variable

and, at high motor speeds, is very low. As a result there may be a tendency for the series relay to chatter. To avoid this condition a line of control based on the use of three-phase secondary series relays is built. A secondary control panel based on this principle is illustrated in Fig. 260. The connections are shown in Fig. 261. This panel comprises a relay and

FIG. 260.—Secondary control panel with three phase secondary current limit relays.

seven accelerating contactors. The relay and six of the accelerating contactors are provided with three-phase secondary current-limit accelerating relays. The primary switching is handled separately by an oil switch or other equipment not shown in Fig. 260.

When the primary switch is opened all the secondary contactors open as their energizing current is taken through a potential transformer connected inside the motor primary

switch. When the primary switch is closed the motor starts with secondary resistors 1, 11, 21 in circuit, the Y being completed at the secondary series relay 1. The rush of starting

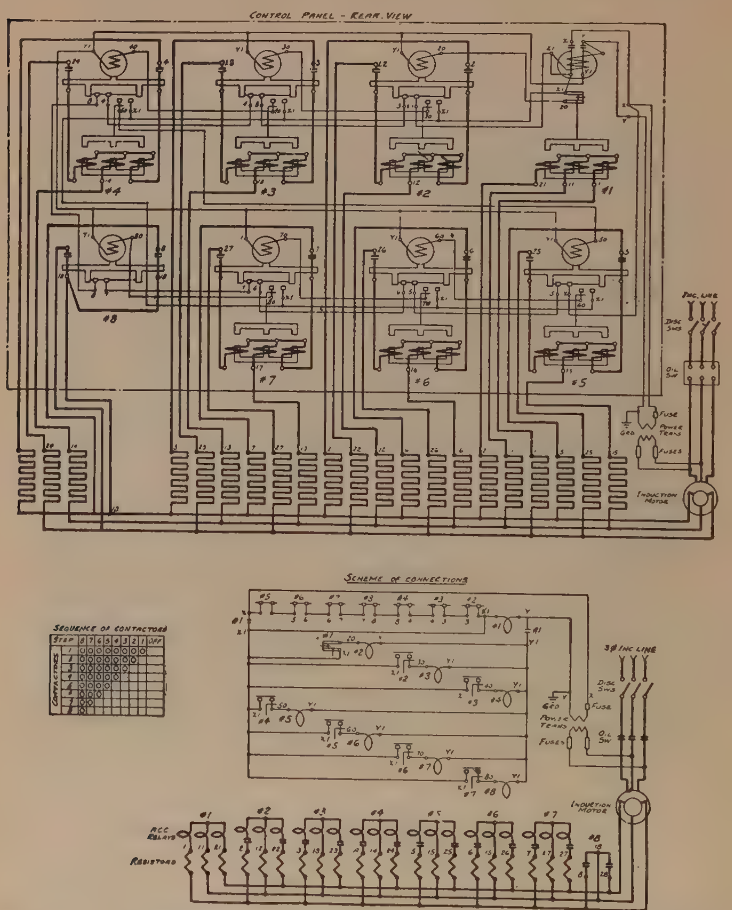


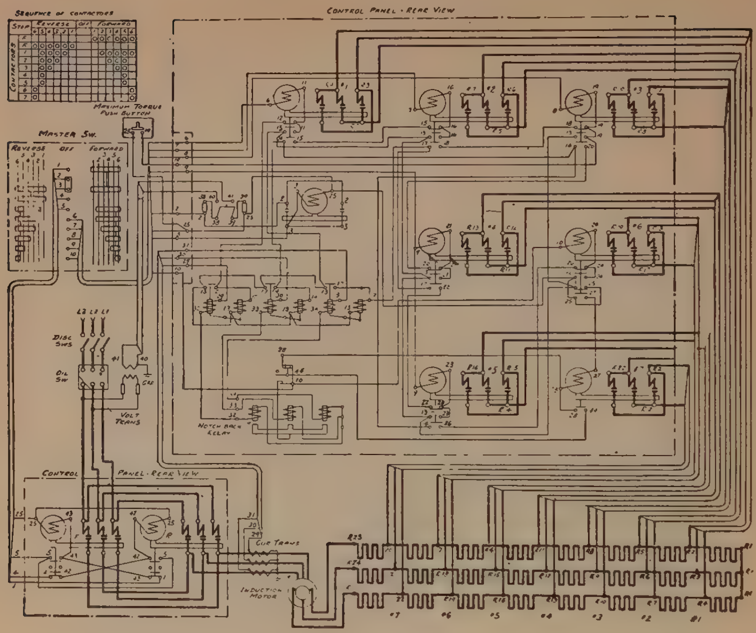
FIG. 261.—Connections for secondary control panel with three-phase secondary current limit relays.

current attracts the armature of this relay, thus holding open the circuit to the closing coil of accelerating contactor 2. When the current in the series relay 1 falls off sufficiently, its armature is released. The closing coil of accelerating

relay 2 is then energized, causing this relay to close. Resistors 2, 12, 22 are now connected in parallel with resistors 1, 11, 21, decreasing the secondary resistance and causing the motor to speed up. Series relay 2 is brought into circuit to complete the Y for this bank of resistors. This relay functions, similarly to its predecessor, to govern the closure of accelerating con-

FIG. 262.—Secondary control panel equipped with notch-back relay.

tactor 3. In like manner the remaining accelerating contactors close in sequence, each governed by the series relay of the preceding contactor. Interlocks are provided so that the voltage relay 1 cannot close in starting unless all accelerating contactors are open. This is accomplished by carrying the closing circuit for this relay through auxiliary contacts on all accelerating contactors in series. These contacts are closed only when the accelerating contactors are open. This arrangement safe-



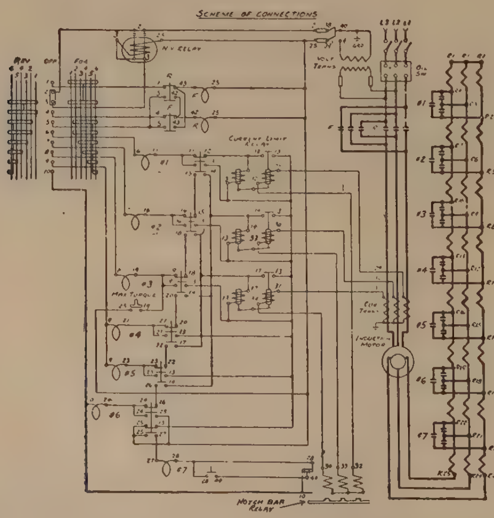


FIG. 263.—Connections for secondary control panel equipped with notch-back relay.

guards against false starting with any of the accelerating contactors closed. A further interlock is provided to insure the operation of the accelerating contactors in the desired sequence. This is done by carrying the closing circuit for each accelerating contactor through an auxiliary contact on the preceding contactor. This auxiliary contact is closed only if the preceding contactor is closed and its series relay released. The series relay functions to hold open one of the fingers making this auxiliary contact.

Overload and no-voltage protection, as well as reverse feature, if desired, must be cared for in connection with the primary control.

Controller with Notch-back Relay.—A magnetic controller for a wound-rotor induction motor, having a number of points of interest, is shown in Fig. 262, the diagram being given in Fig. 263. An oil switch is provided in the primary circuit for overload protection. This is followed by a pair of three-pole primary contactors for reversal of rotation. For the particular application, the forward contactor is normally used, the reverse contactor being used for occasional plugging only, to give a quick stop. The oil switch and primary contactors are not shown in the picture, Fig. 262. As this control is for a large motor there are several secondary accelerating contactors. These function through the action of primary current-limit relays similarly to the more simple control shown in Fig. 257. It is to be noted, however, that the current coils of these relays are energized from current transformers due to the high primary voltage. A notch-back relay is supplied with this control. Its coils are energized from the current transformers in the primary circuit. When the primary current exceeds a fixed value the notch-back relay opens. This, in turn, opens the last accelerating contactor 7. A step of resistance is thus inserted in the secondary circuit causing the motor to slow down. This control is used for motors equipped with flywheels to permit the flywheels to shoulder the peak loads exceeding the value at which the notch-back relay opens.

CHAPTER XX

LIQUID RESISTOR CONTROLLERS

Liquid Resistors.—Pure water is a non-conductor or a very poor conductor of electricity. Water containing chemicals or impurities may be a conductor. The conductivity depends upon the nature and the strength of the solution. Among the materials commonly used to render water conducting are: acids, salt, soda. Of these soda is to be preferred as causing the least corrosive action on the metal container and electrodes.

Water Barrel.—Liquid rheostats find a variety of applications. The well-known "water barrel" is sometimes pressed into service as a starting rheostat for direct-current motors. Quite frequently some form of liquid rheostat is employed to absorb energy, as for testing purposes. These devices are usually of an improvised nature.

Commercial Types.—Liquid rheostats have been developed commercially for use as secondary resistors for wound-rotor induction motors, particularly for the larger motors, 500 hp. and above. There are two distinct types, first, the liquid resistor controller used for starting and controlling the speed of motors subject to frequent starting duty; second, the liquid slip regulator used in conjunction with continuously running equipments. These will be described briefly.

Liquid Resistor Controller.—A liquid resistor controller is shown in Fig. 264, and Fig. 265 is a diagrammatic sketch showing the principle of operation. The lower tank, containing the cooling coils, is the reservoir for electrolyte. The smaller upper tank contains the electrodes. Electrolyte is pumped from the lower tank to the upper tank by the continuously running, motor-driven pump. The resistance is varied by varying the height of the electrolyte in the upper tank. This varies the area of electrodes submerged in electrolyte. The height of the

electrolyte in the upper tank is governed by a weir which permits the excess liquid to flow back to the lower reservoir. Dimensions are such that the upper tank can be nearly emptied very quickly when the weir is lowered. However, when the weir is raised in starting, the liquid level will not rise immediately,

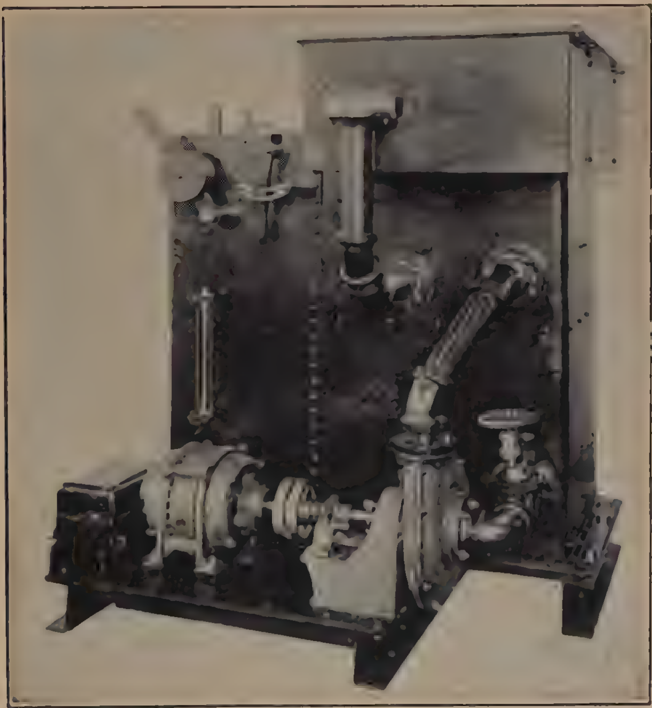


FIG. 261.—Liquid resistor controller for wound rotor induction motor.

being restricted by the rate at which the liquid is pumped. In this way a time element is introduced in the rate of acceleration. This can be adjusted by a valve in the pump discharge line, governing the rate of liquid flow into the electrode tank. A continuous circulation of the electrolyte is maintained by the pump. Circulating water in the cooling coils restricts the electrolyte temperature and disposes of the lost heat. The weir

is moved by a lever from which is also actuated the master switch which governs the primary contactors.

A number of advantages are offered by the liquid rheostat controller as compared with magnetic control for the secondary of large wound-rotor induction motors. The fact that the resistance is reduced gradually, rather than in steps, causes the acceleration to be very uniform and eliminates irregular strains, as on a mine hoist cable, for instance. Exact speed control is possible due to the infinite number of resistance values as com-

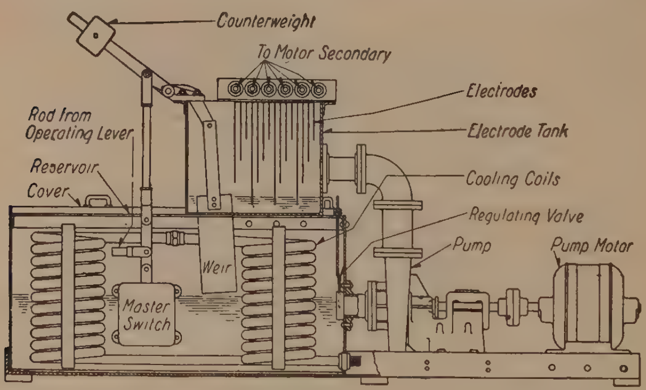


FIG. 265.—Diagram of liquid resistor controller for wound-rotor induction motor.

pared with definite steps of resistance short-circuited by magnetic contactors. The circulating water disposes of the heat which arises from operation at reduced speeds. Alternating-current magnetic contactors for large equipments are rather bulky and severe in operation. The amount of grid resistors required may be large. The cost of the magnetic control is generally higher than the liquid rheostat control. The principal advantage of magnetic control is the absence of liquid and freedom from corrosion troubles.

Liquid Slip Regulator.—The liquid slip regulator is a device for regulating the secondary resistance of a wound-rotor induction motor both while starting and while running. Its primary purpose is to regulate the slip of the motor by varying the secondary resistance to conform with load changes as desired.

Regulators of this type are most commonly employed in connection with motors driving flywheels. It is then desired that the motor handle directly all loads up to a stated amount and that the flywheel absorb all peaks above this. This can be accomplished only by causing the flywheel and motor to slow

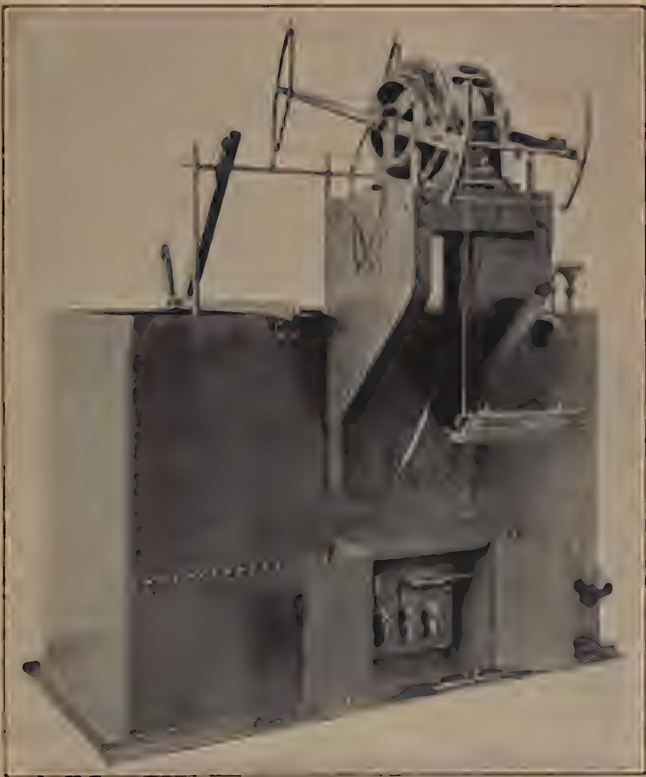


Fig. 246.—Liquid slip regulator for wound-rotor induction motor used in connection with a flywheel.

down sufficiently to relieve the motor of the excess peaks and transfer the peaks to the flywheel.

The liquid slip regulator comprises essentially a tank containing the electrolyte and a movable electrode unit. There are three separate pairs of electrodes, one fixed and one mov-

able electrode for each phase. In one design the fixed electrodes are attached at the bottom of earthenware pots which are suspended from the bottom of the tank. In another design the electrodes are located at the bottom of the tank and are separated by ordinary sewer tile barriers. This construction

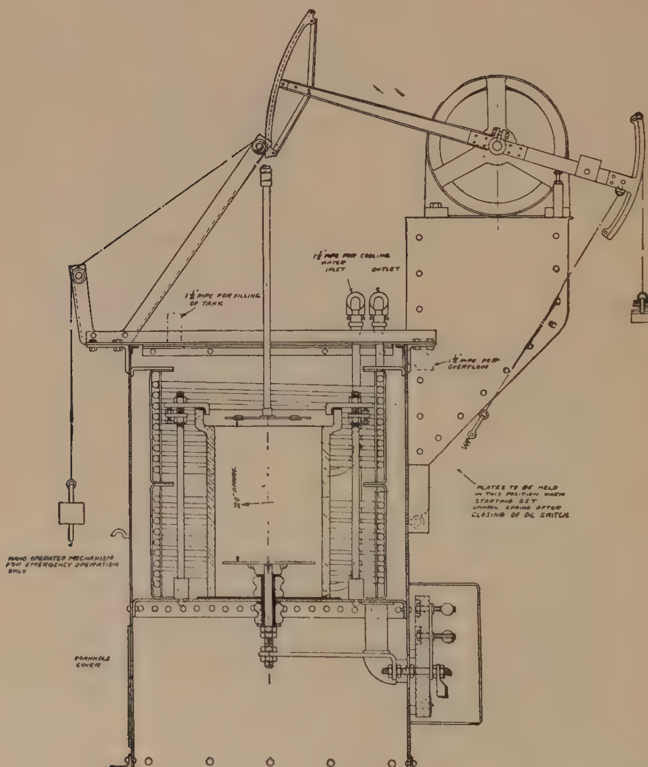


FIG. 267.—Diagram of liquid slip regulator for wound-rotor induction motor.

is shown in Figs. 266 and 267. The stationary electrodes have terminals to which the secondary leads from the motor are connected. The moving electrodes are suspended from a cross member and are electrically connected to form the Y of the secondary circuit. Above the tank is mounted a torque motor which supports two balance arms, one at each end of its shaft.

One end of these arms supports the moving electrodes and the other end supports an adjustable counterweight.

Figure 268 is a schematic diagram showing the electrical con-

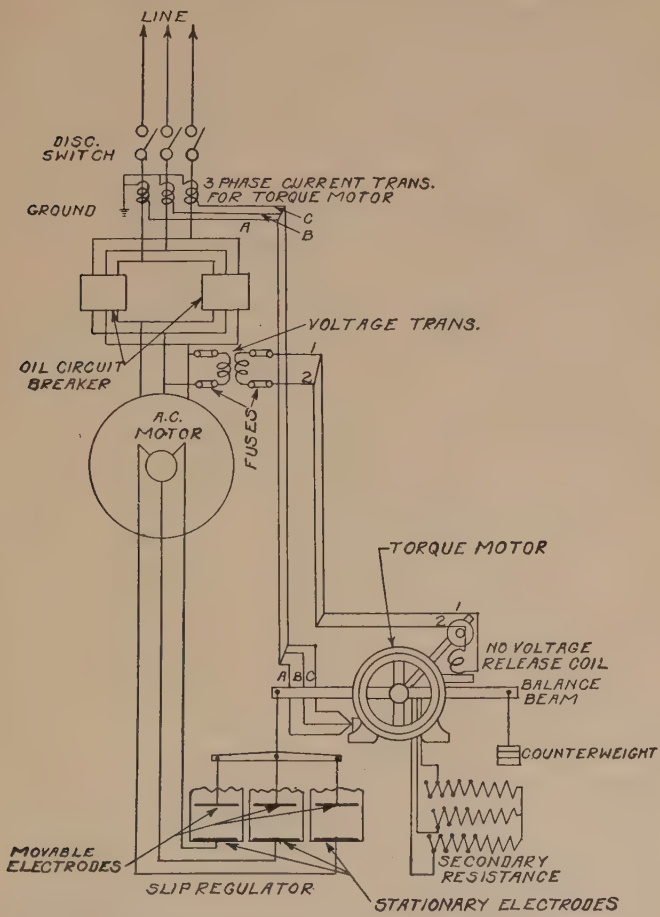


FIG. 268.—Connections for liquid slip regulator for wound-rotor induction motor.

nections of the apparatus. The two oil switches are for reversal of the primary connections. It should be noted that the torque motor is supplied from a special current transformer connected

in the primary circuit of the main motor. The torque developed by this motor therefore varies with changes in load of the main motor. The moving electrodes are slightly heavier than the counterweight so that the torque motor must exert an effort in order to lift the moving electrodes and separate them from the stationary electrodes. When the main motor is lightly loaded, the fixed and moving electrodes nearly touch each other, so that the secondary resistance is very small. The instant a peak load occurs, sufficient torque is developed in the torque motor to separate the plates. This introduces secondary resistance and increases the slip. A small movement of the electrodes causes a large increase in resistance, if the liquid is of the proper conductivity.

Both the voltage and the current of the torque motor change with the load current of the main motor. The torque of the latter varies as the square of the main motor current. A small change in main motor load, therefore, produces a relatively large change in the effort of the torque motor, which is thus sensitive in action. The plates will continue to separate so long as there is a tendency to overload the motor. After the peak is over, the moving electrodes approach the stationary electrodes at such a rate as to maintain the main motor current at the maximum value for which the regulator is adjusted, until the flywheel is brought back to maximum speed.

Slip Regulator Application.—There are three common methods for controlling wound-rotor induction motors operating in connection with flywheels. The most simple method employs fixed secondary resistance sufficient to cause 10 to 15 per cent slip at full load. This arrangement is commonly employed for motors of small and medium sizes. It is open to some disadvantages. The flywheel effect is not most effectively used in that the flywheel begins to function as any load comes on. It may therefore be slowed down and much of its energy absorbed before peak load values are reached. As the secondary resistor is always in circuit, losses occur at all loads, decreasing efficiency. The amount of slip is limited so that peaks cannot be restricted to a definite value.

Magnetic control with a notch-back relay is often used. This is not as responsive in action as the liquid slip regulator

and does not permit of so wide a range of values of secondary resistance.

With slip regulator control the motor maintains its speed under load, having the characteristic curve AC, Fig. 269. Up to the point C on this curve, the motor assumes nearly all the load and conserves the energy in the flywheel. The motor load is then restricted to this value, the action of the regulator being such as to throw the excess load onto the flywheel as the speed drops. After the peak is over the motor continues at this load

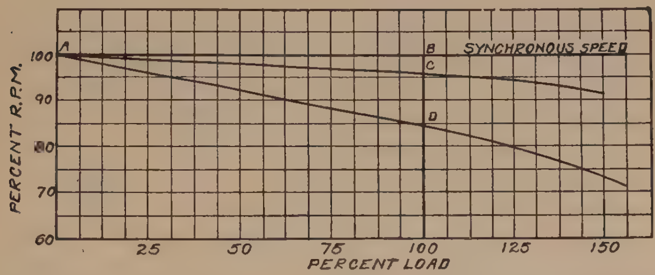


FIG. 269.—Speed regulation of wound-rotor induction motor with liquid slip regulator. Curve AC shows motor speed with secondary shorted giving a slip at full load of 3 per cent. Curve AD shows motor speed with resistance in the motor secondary to give a slip of 15 per cent at full load.

until the flywheel is brought back to speed C. Then the load drops off along the curve C–A.

The point at which the slip regulator functions to relieve the motor may be adjusted by changing taps of the current transformers, by adjusting the counterweights and by adjusting the secondary resistance of the torque motor. Small adjustments are made by the counterweights. As the regulator limits the motor power developed it is obvious that the regulator must not function too quickly with respect to the average demand as it will then be impossible to obtain sufficient output from the motor to maintain operation. With a given load cycle to be performed, a given flywheel and a limited permissible slowing down of the motor, the energy which the flywheel can convey is definitely restricted. The motor must assume the balance of the load during the peaks. Periods of light load,

during which the flywheel may be accelerated, must be sufficient to offset the demands made upon the flywheel. With these limitations in view, the slip regulator may well function at a minimum permissible load in order to smooth out the demand upon the electric power system as much as possible.

In starting a wound-rotor induction motor equipped with a slip regulator the electrodes are separated their maximum distance. The current inrush in starting is determined by this distance and by the conductivity of the liquid. As the starting current falls off, the moving electrodes approach the fixed electrodes, maintaining the current at value C until the flywheel is fully accelerated. A no-voltage trip releases an auxiliary counterweight which causes the electrodes to separate whenever the power is off. This protects against starting the main motor with secondary resistance short-circuited.

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CHAPTER XXI

OPERATION OF MOTORS IN PARALLEL OR SERIES

Where Parallel Operation Is Applicable.—Where continuous operation is imperative, the use of two motors in parallel offers possibilities for emergency operation with a single motor. Sometimes each motor is capable of handling the entire load. This means a double investment. It is often preferable for the two motors combined to handle the normal load with some margin, a single motor running at reduced speed and perhaps slightly overloaded. Instances of applications of this sort are the hoist on a ladle crane or the tilting motion of a metal mixer in a steel mill.

Two small motors may be preferable to one only because of their size. The smaller units may be standard and duplicate others in a plant, whereas a single large motor would be special to the plant and might require separate spare parts to be carried. It may frequently be possible to combine motors on hand rather than to purchase a new larger unit. Mill-type motors are not built in very large units, it usually being preferable to combine two smaller ones. Smaller motors require less space and may be fitted in where space is at a premium. They weigh less, are more easily handled and may be more readily dismantled and their parts removed. Two motors, having armatures of small diameter, may have materially less inertia than an equivalent single motor.

Not infrequently, a machine is spread out, the main load occurring at separated points that must run in unison. Or the machine may be symmetrical, in reality comprising two parts that must operate together. Such cases lend themselves to the use of two motors with attendant decrease of shafting and transmission equipment. A case of this kind may be seen in the bridge of a traveling crane where two motors drive the two end trucks but are coupled by a shaft running across the

bridge. A more extreme case is that of the ore bridge, the two ends being moved by motors operated in parallel without mechanical connection other than that through the track wheels and tracks.

A group of machines may be driven by two motors connected in parallel so that together they handle the load during peak conditions. The larger motor alone will perhaps care for ordinary service, while the smaller one is used for overtime and night work. There are a number of such possibilities for parallel operation.

Where Series Operation Is Applicable.—Some of the reasons for using two motors in parallel apply equally well if the two are connected in series. There are other advantages peculiar to the series connection. The control of two motors, in series, is simple and inexpensive, being practically equal to that required for one of the two motors. Two motors in series develop starting torque equal to that of two connected in parallel, but with less total current input, since the same current passes through both. It is a common practice to connect in series two 230-volt motors, placing the combination across 230 volts. The motors thus attain but half normal speed. Where the drive is through gears, the ratio with the motors in series will be half that when they are in parallel if the same running speed is to be attained. The same starting torque is developed by a motor, whether operated alone or in series or parallel with another. The power required to accelerate a machine under fixed conditions is a definite quantity whether the motors are connected in series or parallel. It does require more power, however, to accelerate a motor itself to full speed than to half speed, as inertia of the armature and pinion must be overcome. Consequently, in rapidly reversing drives where the motors attain considerable speed and their inertia is a serious factor, series connection may lead to more rapid operation.

Combination Series-parallel Operation.—Motors are sometimes arranged for operation either in series or in parallel. Traction service is a notable example. Here the motors are brought up to half speed while connected in series. If higher speed is desired, they are then connected in parallel. This

arrangement is simple and economical of power as it reduces the resistance losses of acceleration. Another instance of series-parallel operation is the screw-down application in steel mills. The motors may be arranged for series connection while screwing down, where slow speed, short movements and accurate adjustment are desired. When lifting the rolls, the motors may be connected in parallel, thus securing maximum speed.

Requirements for Parallel and Series Operation.—When motors are to operate together, the first requirement is that each assume its proper share of the load. If they are to be connected in series, it is necessary that they be rigidly connected mechanically, since otherwise one might assume more than half voltage and speed up while the other slowed down. Motors connected in series must of course pass the same current. If mechanically connected, they will operate at the same speed (with equal gearing) and will have equal voltage at their terminals. They must therefore divide the load equally. It will be seen that, with this arrangement, the units must be of equal size.

When motors connected in parallel drive a single load, each is connected across the line and is free to pass its own load current independently. Load division then becomes a matter of relative speed-power characteristics. The two machines together will drive the load at a speed dependent upon their combined pulling ability. Each will take a load corresponding to this speed on its own speed-power curve. Let us see how this works out.

Parallel Operation of Constant Speed Motors.—Curve X of Fig. 270 is the speed-load curve of a shunt-wound direct-current motor. Curve Y of the same figure is the speed-load curve of another similar motor. These motors are mechanically connected together and to the same load. Being connected together, they will run at the same speed, which, for a given load, will be 610 r.p.m., as shown by the dotted line *aa*. This speed corresponds to approximately 85 per cent load with one of the motors, whereas with the other, this speed corresponds to about 30 per cent overload. It is evident that these motors will not equally divide the load. If it is possible to change their relative speeds, as by a change of gears, or by turning

off the pulley of one motor, it may be possible to attain equal load division. The motors are then carrying the same load, but operate at slightly different speeds. It should be noted that with this arrangement it would be possible for the two motors to drive proportionately at one load but to fail to do so at another. This is due to differences in speed regulation. A motor having good regulation tends to hold up the speed as the load comes on. If such a motor be paralleled with one

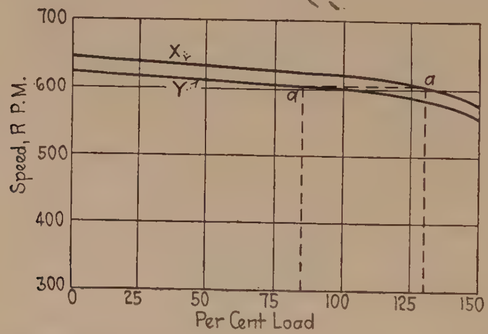

FIG. 270.—Speed-load curves for two shunt motors in parallel.

having a marked falling off in speed under load, the first will assume proportionately more and more of the work as the load increases. Hence such a drive is not satisfactory. For this reason it is not desirable to parallel mechanically a shunt-wound motor with a compound-wound motor or a squirrel-cage motor with one of the wound-rotor type.

In Fig. 270 two shunt motors are shown having similar characteristics, yet differing in values. It is a difficult matter to find two motors having identical characteristics. Although they may be built to the same specifications, their performance will vary. The air gaps may be a little different, affecting the flux. The shunt coils may easily differ slightly in resistance. The cast portions of the magnetic circuits may differ; the brush positions or brush contact may not be the same, or the leads to one motor may be longer and have greater voltage drop. There will always be some differences in performance, ordinarily not noticeable, but sufficient to have a marked influence when motors are paralleled. Induction motors are likely to

more closely duplicate performance than are direct-current machines.

Parallel Operation of Varying Speed Motors.—The same general conditions hold with compound-wound and series-wound

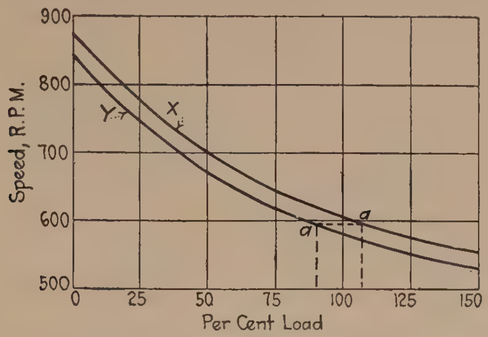

FIG. 271.—Speed-load curves for two compound motors in parallel.

motors as with shunt-wound machines. Figure 271 shows the curves for two compound motors of like design, while Fig. 272 shows the curves for two similar series motors. It is to be noted that, owing to greater pitch of the curves, representing

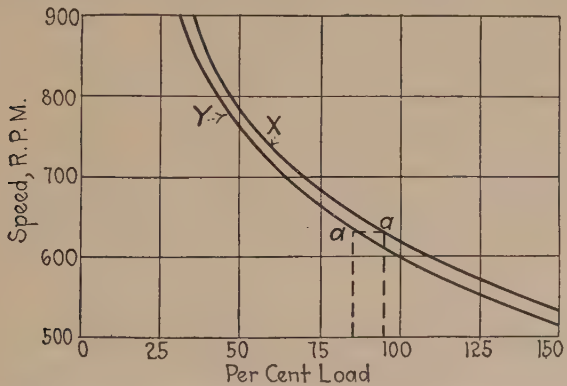

FIG. 272.—Speed-load curves for two series motors in parallel.

poorer speed regulation, compound motors operated in parallel will divide the load more equally than shunt motors, while the load division with series motors will generally be quite good. Squirrel-cage induction motors are comparable with shunt

motors in this respect, while the wound-rotor type with external resistors is similar to the compound-wound machine, dividing the load more uniformly the poorer the speed regulation.

Indirectly Paralleled Motors.—Sometimes motors are paralleled in effect, through the machines which they drive. Thus, two centrifugal pumps or two fans may discharge into a common system. In a case of this kind it is desirable that the driven equipment, in combination with the motor, have a drooping load characteristic in much the same manner as above explained as applying to two motors mechanically connected to the same load. Thus, two fans which have a drooping quantity-head curve may discharge into a common system and will approximately divide the duty but, if the quantity-head curves are flat and the fans are driven by motors having flat characteristics, the load division may be quite unequal.

Control Considerations.—It may be of interest to note a few points concerning the control of motors connected in series or in parallel. Shunt motors are not often operated in series, the balancer set on a three-wire system being perhaps the most common application. Here the shunt fields are connected across the outer lines or interconnected, and a starting rheostat is inserted in the armature circuit. When shunt motors are operated in parallel, it is satisfactory to use a single starting rheostat large enough for the two motors. If fuses are installed ahead of the starter, they will not protect the individual motors, and it is well to place the fuses in each motor circuit. Squirrel-cage induction motors may be connected in parallel from the same auto-starter, but the fuse protection will be faulty and overload relays in the individual motor leads will be preferable. Two wound-rotor induction motors, operated in parallel, may well have a single primary controller but separate secondary controllers are advisable. Each rotor is, in effect, a separate generator and the secondary circuits may be paralleled only if the phase relations are correct. If the rotors be permanently mechanically connected in positions to afford proper phase relations, a single secondary controller may be used.

Series motors, when connected in series, may be controlled

by a single drum or magnetic controller, the same as would be used for one motor. There are several ways to control two series motors connected in parallel, not all desirable. It is possible to use a single controller, connecting the series fields in parallel and the armatures in parallel as indicated in Fig. 273. The fault with this arrangement rests in the difficulty in securing equal division of current through the two series fields. These fields are of low resistance and slight differences in them or their leads will cause unequal division of current. The field passing the lesser current will be the weaker, and the corresponding armature will run faster and tend to assume most of the load. It is found in practice that motors connected in this way divide the load very poorly, one motor taking nearly all the load in some cases.

Two series motors may be connected in parallel according to the scheme of Fig. 274, using two sets of directional switches with but one accelerating resistor and one set of accelerating switches. This arrangement is entirely satisfactory when accelerating the motors from rest, but is not good for "plugging" or reversing service because the local loop circuit, comprising the two armatures and two series fields, is subject to some voltage due to differences in the counter-voltages of the two motors when they are plugged. The local voltage may be small, but is sufficient to send enormous currents through the local low-resistance circuit. See Chap. XXIII, page 467.

The best arrangement for parallel operation of two series motors is shown in Fig. 275. Here we have separate directional switches for each motor and separate resistors. The presence of the resistors in the local loop circuit greatly reduces the local current when "plugging." An arrangement such as shown in Fig. 275 may be obtained either through the use of two entirely separate controllers or by a single controller having two-pole magnetic switches throughout, one pole of each switch being for each motor. The first-mentioned arrangement is preferable as being standard and offering advantage in case of failure of one controller; while the double-unit controller offers some advantage by insuring the same rate of acceleration for both motors, a condition that may not be attained in case two separate controllers are used.

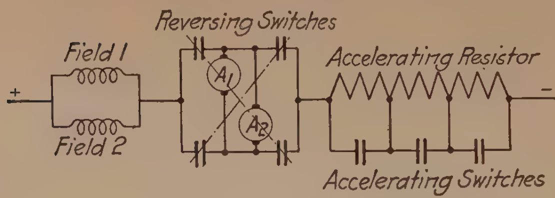

FIG. 273.

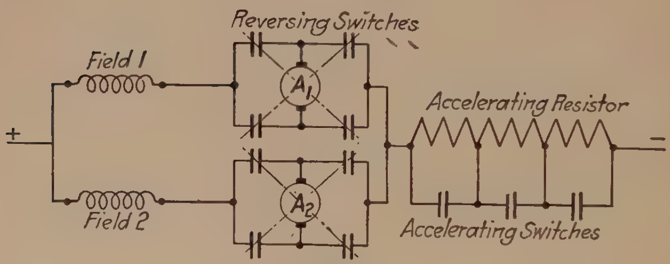

FIG. 274.

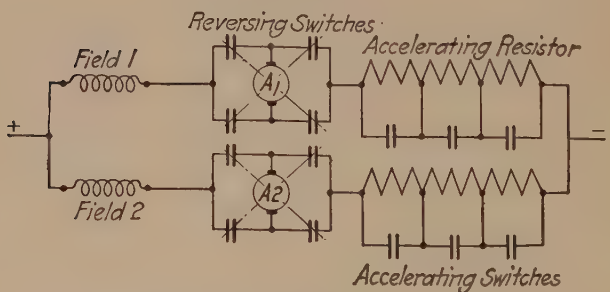

FIG. 275.

FIGS. 273, 274, 275.—Different methods for connecting series motors in parallel.

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CHAPTER XXII

THE USE OF FLYWHEELS IN THE APPLICATION OF ELECTRIC POWER

Equalization of Demand.—Many types of machines require a heavy draft of power during a portion of their cycle of operation, together with a lesser demand over other portions of the cycle. A number of advantages may accrue through ability to equalize this demand upon the driving motor and upon the source of electric power.

A motor sufficiently large to handle the peak demand might represent an excessive investment. Moreover the average load would be too low for best efficiency and power factor. Equalization of load may lead to reduction in motor capacity. Not only is motor capacity affected, but also the capacity of control, conversion, transmission and generating equipment.

A uniform demand for power leads to economical generation or purchase. Where turbines and boilers can be maintained at economical loading, a distinct gain in economy results. The price of purchased power is usually based upon demand as well as consumption. Decreased demand may bring about a lower rate for the power actually consumed. Where large powers are involved, utility companies may restrict the peaks permitted.

Flywheel Energy.—A flywheel is a means for storing and delivering energy for the purpose of transferring the demand upon the motor from one instant to another. It should be borne in mind that the flywheel can deliver only that energy originally received from the motor. A flywheel stores energy by virtue of its velocity. The energy stored is proportional to the square of the velocity. Energy can be imparted to the flywheel only by increasing its velocity and can be delivered only by decreasing its velocity. The curves shown in Fig. 276 indicate the variation in stored energy as a flywheel is accel-

erated to full rated speed and show also the per cent of this stored energy which may be recovered by permitting the flywheel to slow down or slip through a given increment of speed.

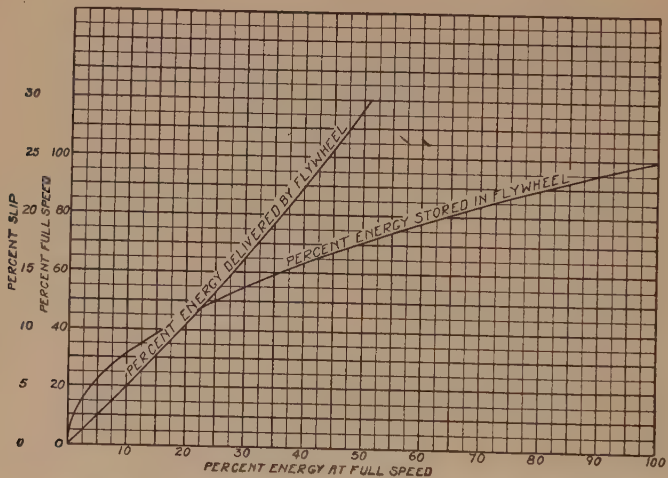

FIG. 276.—Stored energy in a flywheel at different speeds.

The formulae which apply to flywheels follow:

$$E=\frac{WV^2}{64.32}\text{ ft.-lbs.}\qquad E=\frac{WV^2}{35,400}\text{ hp.-sec.}$$

$$E=\frac{WR^2N^2}{5870}\text{ ft.-lbs.}\qquad E=\frac{WR^2N^2}{3,230,000}\text{ hp.-sec.}$$

where W = weight of flywheel, lbs.;
R = radius of gyration, ft.;
V = linear velocity at radius of gyration, ft. per sec.;
N = angular velocity, r.p.m.;
E = energy stored in flywheel.

Flywheel Construction.—Any revolving mass has some flywheel effect and in some cases this effect in the actual machine members is, or can be made, sufficient to meet the requirements. Flywheels are constructed from cast iron or cast steel or built up

from laminated steel plates. Cast-iron wheels are used only for small sizes or where low speeds are permissible. Cast-steel wheels are used extensively for large powers at moderate speeds. Plate wheels are used for large powers at higher speeds. The limitation rests largely in the permissible linear velocity at the periphery of the wheel, due to the action of centrifugal force. This effect is proportional to the square of the velocity, hence flywheels should not be permitted to exceed greatly their rated speeds and overspeed protective devices are desirable in many instances. The maximum safe speeds used for flywheels of the different types are as follows:

Type of wheel	Linear velocity at periphery, feet per minute	
	Normal	Overspeed trip
Cast iron	6,000	6,600
Cast steel	16,000	20,000
Laminated plate	20,000	24,000

It is obviously desirable that flywheels be operated at speeds as high as may be feasible. The weight and cost of the flywheel, shaft, bearings and foundations are thereby reduced and the losses are also minimized.

Flywheel Selection.—In determining a flywheel application the rotational speed and the amount of permissible slip are usually known, together with the amount of energy necessary in horsepower-seconds or foot-pounds. A decision is necessary as to the type of wheel. This leads to selection of peripheral speed and thus to rim diameter. The chart, Fig. 277, may now be used to determine the weight necessary. First select point on curve corresponding to allowable speed reduction, then proceed horizontally to the left to intersection with line representing wheel radius, thence downward to line corresponding to normal full speed, thence horizontally to line representing energy required, thence down to reading of weight. The values given apply to plate wheels. For cast wheels the total weight will be 80 to 90 per cent of that required in a plate wheel, due to more effective disposition of material at the rim. An exact

determination may be made by determining relative radii of gyration. The analysis may be based on the formula:

$$\text{Radius of gyration} = \sqrt{\frac{R_1^2 + R_2^2}{2}},$$

where R_1 and R_2 are the outer and inner radii of rim, hub or web, respectively.

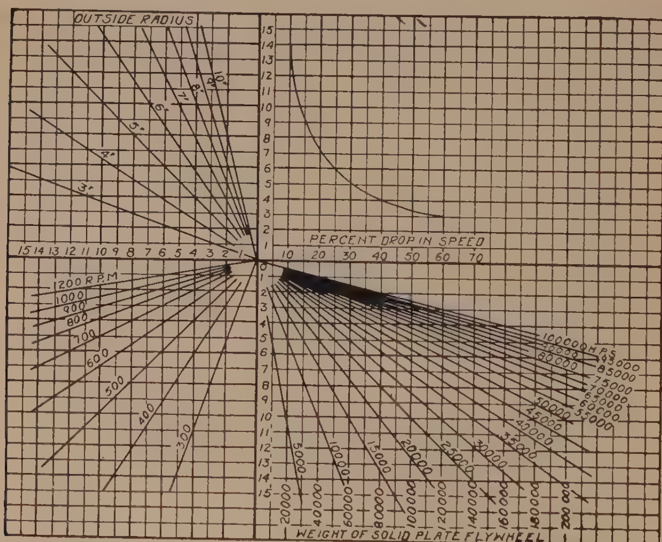

FIG. 277.—Chart for flywheel determination.

Application.—Flywheels may be used directly in connection with the motor and attached to the motor or driven machine. Common applications of this type are punch presses and shears and some continuous steel rolling mills. Most frequently the flywheel is mounted on a shaft coupled to the armature shaft and rotating at the same speed. Sometimes the flywheel is mounted on a driven shaft which is geared to the armature shaft. For a geared drive, this practice has the advantage of relieving the gearing of peak loads and shocks. However, if the driven shaft is a lower speed shaft, as is frequently the case, a larger flywheel is required.

Flywheels may be used in an indirect manner for load

demand equalization. This is done extensively through the use of motor generator sets equipped with flywheels, notably in the Ilgner system. Most commonly the motor generator set supplies power to one or more motors having widely fluctuating loads. Mine hoists and rolling mills are the most common applications although ore-handling gantry cranes have been supplied from equalizing sets. The primary purpose of the flywheel for such a set is to equalize the demand upon the source of electric power supply. In many cases the cycle is such that the drive motor acts as a generator over a portion of its cycle and thus returns power to the flywheel through the temporarily motorized generator of the set. This occurs in some mine-hoist work when the hoist overhauls and in a reversing mill motor drive when the motor, in reversing, returns its kinetic energy to the system.

Flywheels are occasionally used as a source of energy storage to be called upon in case of failure of electrical supply. Such is the case in mine-hoist service where the Ilgner set may deliver sufficient energy to complete one or more hoisting cycles and thus prevent possible imprisonment of men in the shaft.

In the selection of a flywheel for a given cycle of work, a choice is possible in the degree of load equalization. Where peaks are of long duration a very large flywheel would be required to be effective. Where peaks are relatively short, a flywheel may absorb them quite completely. As a general rule, the more complete the equalization of demand over a cycle, the heavier the flywheel required. The heavier wheel represents higher investment and greater power losses but lowers the demand. The proper size of wheel then depends largely upon the relative value or importance of demand and power consumption.

Losses.—The losses incident to flywheel operation are bearing friction and windage, together with motor losses incident to the necessary slip. Bearing and windage losses have been found to have the following approximate values:

Plate wheel—	Exposed	1.25 hp. per ton
	With housing	1.00 hp. per ton
Cast wheels—	Exposed	1.50 hp. per ton
	With housing	1.25 hp. per ton

The windage loss of cast wheels with spokes, operating at high speeds, may be reduced by filling in between spokes with plates to more nearly approach smooth wheel conditions.

Motor Speed Control.—The fact has been mentioned that a flywheel can deliver energy only while slowing down, the amount delivered depending upon the extent and the rate of delivery depending upon the rate of slow-down. To obtain the full measure of benefit from a flywheel it is necessary that the motor and control be so arranged that the speed will automatically drop through a greater range, with load peaks, than is the usual practice for such motors when no flywheel is used. A direct-current compound-wound rotor has an inherent drooping characteristic adapting it for flywheel operation. With induction motors, there are three devices used, namely, fixed secondary resistance, the notch-back relay and the liquid slip regulator. Fixed secondary resistance may take the form of a high resistance rotor or external resistors continuously in circuit with a wound rotor. This method is relatively simple. It is well adapted and most used with the smaller drives such as shears and punch presses. The disadvantage of this arrangement lies in the fact that the speed drops under all loads so that, in the case of a load gradually applied, the flywheel may have delivered a considerable portion of its energy before the peak demand occurs. Moreover, due to the high slip at all loads, the secondary losses may be excessive.

The ideal speed control for a flywheel application is one in which the speed is well maintained for all moderate load values but, when overloads arise, the speed will tend to drop rapidly. This can be accomplished, with a wound-rotor induction motor, by maintaining low secondary resistance for all moderate loads and by increasing the secondary resistance when the load reaches a stated value. This, in turn, can be accomplished by either the notch-back relay or the liquid slip regulator.

It has been previously stated that the energy delivered by a flywheel depends upon the range of speed through which it is operated. Small wheels are ordinarily operated through a range of about 10 per cent. Larger wheels may be operated

through a wider range, up to 15 or 20 per cent. For emergency use a speed drop as high as 35 per cent may be utilized. It should be noted that 15 per cent slip corresponds to utilization of 28 per cent of the flywheel energy. With 20 per cent slip the energy delivered is 36 per cent. The gain due to greater slip constantly decreases. The proper speed range is a compromise. Wide range may increase the cost of motor and control and materially lower the efficiency due to slip losses. The amount of speed variation permissible may be determined by the requirements of the driven machine which may require that the speed be maintained within definite limits.

Protection.—It may be noted incidentally that energy stored in a flywheel is not subject to control. For this reason, overload protection applied to the driving motor does not afford protection to the driven machinery. Care must be taken not to overstress a punch press or shear equipped with flywheel drive, lest a damaged shaft or housing result.

Cyclic Loads.—The previous discussion has dealt largely with flywheels arranged to equalize loads over a work cycle. Flywheels are sometimes used for a somewhat different purpose. With such loads as reciprocating compressors and pumps, the torque required during a revolution pulsates regularly. Particularly where synchronous motors are used to drive, this torque variation tends to set up variations in angular velocity which may lead to cumulative swinging or hunting.

The amount of variation in angular velocity depends upon the range of torque values and upon the inertia of the revolving parts. Variation in velocity causes the rotor to take positions behind or in advance of normal for uniform rotation. In the direct-connected synchronous motor this involves displacement of the rotor-field poles with respect to the uniformly revolving stator field. This causes momentary variations in torque developed by the motor.

The combination of the two varying torques, namely, load torque and motor torque, tends to set up oscillations. The extent of these oscillations, in practice, depends largely upon design factors in the motor which influences its angular displacement and depends also upon the inertia of the rotating

parts. Should these factors be such as to cause the frequency of the load torque variation and the natural frequency of the motor to coincide, excessive hunting may result. This condition may be most readily adjusted by varying the inertia of the rotating parts to vary the natural frequency of the motor. This may be done through use of a flywheel. This question is discussed at some length in Chap. VII, page 144.

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CHAPTER XXIII

ELECTRIC MOTOR BRAKING[1]

Braking Functions.—The electric motor may be employed not only to accelerate and drive machinery but also to decelerate and stop it. A distinction may be drawn between three types of braking. In lowering an unbalanced load, as with a crane, elevator or mine hoist, the motor merely restricts the speed and restrains the overhauling load. In an elevator drive or a skip-hoist drive the motor often serves to reduce the speed from full running value to a lower definite value as the end of the travel is approached. With some machine tools and in many steel mill applications, the screw-down, for instance, motor braking is used to bring the motor to a stop. Motor braking may thus be used:

1. To restrict speed of overhauling loads.
2. To cause definite slow-down.
3. To stop.

Electric and Mechanical Braking.—Braking may be accomplished, with a motor drive, either by the motor itself or by an external brake. The motor acts by torque electrically developed in a direction opposing the motion. The brake acts mechanically through friction.

Plugging.—The direction of rotation of a direct-current motor is reversed by reversing armature connections. The rotation of an induction motor is reversed by interchanging primary phase leads. If armature or phase leads be reversed while the motor is running, the motor will develop torque opposing rotation, bring the rotor to a stop and start it in the

[1] Some of the subject matter in this chapter has been mentioned at other points in the text, but is included here in order to make a more complete treatment under a single heading.

reverse direction. This procedure is termed "plugging" a motor.

Regenerative Braking.—If a direct-current shunt motor be driven above normal speed it will revert into a generator and will tend to deliver power to the electric system. It therefore requires mechanical power for its drive and acts as a drag. In like manner, an induction motor driven above synchronous speed becomes an induction generator, delivering electric power and demanding mechanical propulsion. Braking by the above methods, in which electric power is returned to the electric system, is commonly termed regenerative braking.

Dynamic Braking.—If a direct-current motor, while running, have its armature disconnected from the line and then short-circuited through a resistor, with the field excited, the motor acts as a generator and circulates current through the armature and the resistor. The energy absorbed in the resistance of the armature and its external circuit, is translated from mechanical energy by the motor. Braking by this and similar means, wherein the motor is converted into a generator dissipating energy in external resistors, is commonly termed dynamic braking.

Action in Plugging.—Having outlined the various methods of motor braking, we will consider a little more in detail the nature of their action. When a direct-current motor is running, it generates a counter-voltage which opposes and nearly equals line voltage. When the motor is plugged, the counter-voltage continues in its previous direction so long as rotation continues. The impressed voltage is reversed by reversal of armature leads. The impressed volts and counter-volts are therefore temporarily additive. The voltage existing momentarily across the armature and starting resistor in series may therefore be nearly twice line voltage. As the motor slows down, prior to reversal, the counter-voltage decreases and lowers this total voltage. It should be evident that, to restrict the armature current at the instant of plugging, series resistance materially higher than starting resistance is required. Plugging is often mentioned as a deplorable practice. This is true in the case of control which is designed for starting duty only and which does not provide sufficient series

resistance to restrict the plugging current peak to a safe value. It is also true if the series resistor, although suitably provided for plugging, is cut out too rapidly. Plugging as practiced with a suitable plugging resistor added to the starting resistor and with features preventing too rapid short-circuiting of these resistors, is an entirely commendable practice. A disadvantage of plugging lies in the fact that the motor is not only stopped, but reversed. If it is desired to merely stop the motor it is necessary to cut off the current at exactly the right instant either manually or by a relay or governor. An advantage of plugging lies in the fact that a strong decelerating torque is maintained by the motor down to and through the point of reversal. The proper value of total series resistance, inclusive of starting and plugging resistance, may be ordinarily approximated by dividing 150 to 175 per cent of line voltage by the permissible current peak. Line voltage plus counter-voltage usually totals 150 to 175 per cent line voltage, momentarily. It may be noted that if a series motor is plugged from a high speed, the combination of high speed and strengthened field caused by the increased plugging current, will greatly increase the counter-voltage and consequently increase the momentary voltage peak and plugging current inrush. For such cases a higher plugging resistance is required. This is apparent from the curves shown in Fig. 185, Chap. XV, showing speed-current characteristic of a series motor with various values of series resistance. The values below the zero line show the plugging current at any speed with the amount of series resistance as shown. Incidentally it may be remarked that an adjustable speed motor should not be plugged on a weak field. If plugged from high speed, an extreme plugging voltage and current peak will result.

The plugging of induction motors is a less frequent practice as they are less commonly used for drives requiring manipulation. The squirrel-cage motor draws a high current peak when starting from rest. It will draw a somewhat higher peak if plugged. The high resistance cage motor may be adapted for plugging duty. The wound-rotor motor may be and is quite commonly arranged for plugging. In order to restrict the plugging current peak, extra secondary resistance is required

just as in the case of the direct-current motor. It should also be noted that the voltage and frequency in the rotor circuit are nearly double the values existing when starting from rest. If a wound-rotor motor is to be plugged, it may require special insulation of the rotor windings and extra clearances at the collector rings and brushes. The same general conditions governing plugging practice apply in the case of both alternating- and direct-current motors.

Regenerative Action.—All that is necessary to convert a direct-current motor to generator action is to increase the speed or strengthen the field to such a point that the counter-voltage

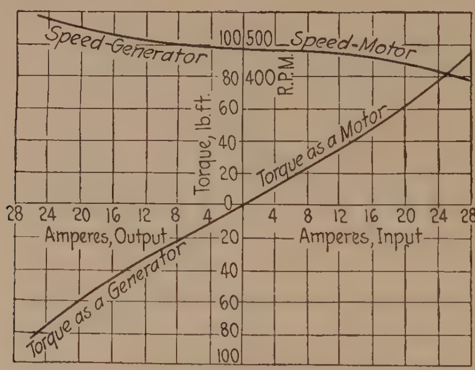


FIG. 278.—Speed-current and -torque characteristic of a shunt motor, showing generator action.

generated is greater than impressed voltage. Figure 278 shows the speed-load curve of a motor from which it may be seen that a slight increase above no-load speed will cause generator action. This applies in the case of a shunt-wound motor. A compound motor has a steeper characteristic so that a greater increase in speed is necessary to cause an appreciable generator load. If a compound-wound motor is used in connection with an overhauling load the series field is generally cut out, during running intervals, to give a shunt characteristic. A series motor cannot be employed as such in this capacity as the load cannot be removed without causing excessive speed. A shunt characteristic is necessary to obtain regenerative action without wide speed change.

An interesting application of regenerative braking occurs in the case of the reversing motor employed for driving steel mill rolls. Ward-Leonard variable voltage control is employed. The slow-down prior to reversal is obtained by weakening the field of the generator unit. This causes the motor unit to regenerate and return its energy to the generator unit by regenerative braking action.

An induction motor, driven above synchronous speed, becomes an induction generator. The amount of speed change necessary to produce an appreciable load change depends upon the motor characteristic. A squirrel-cage motor with a flat speed-load curve will change from motor to generator action with a relatively small speed increase. A high resistance cage motor or a wound-rotor motor with external resistors in circuit will not produce effective generator action except as a result of a considerable speed increase. This is of particular interest in connection with electric elevators where a flat characteristic is desirable for regenerative braking but where considerable secondary resistance is necessary to produce the desired starting torque.

Dynamic Braking with Shunt and Compound Motors.—Dynamic braking is employed for restraining, for slowing down and for stopping. These applications will be considered in reverse order. To stop a direct-current motor by dynamic braking, the armature is disconnected from the line and then short-circuited through resistors. The braking current is proportional to the voltage generated in the armature. This, in turn, is proportional to the speed and the field flux. The current is also inversely proportional to the resistance of the armature and external circuit. The braking torque is proportional to the armature current and the field strength. Dynamic braking can be quite readily accomplished with a shunt- or compound-wound motor, the braking field being supplied by the shunt winding. Figure 279 shows the principal connections of a reversing control for a compound-wound motor, with dynamic braking used for stopping. Note that the series field should be omitted from the braking circuit but the interpole should be included in the circuit. To obtain effective dynamic braking on a compound-wound motor a liberal shunt field winding is necessary to

supply a stiff field. To obtain effective braking with a weak shunt field, excessive armature current is required to develop the desired torque. It should be noted that, with any type of motor, as the motor slows down the counter-voltage and current fall off so that the braking effect reduces to a low value at low speed. Where it is desired to maintain the braking torque, the braking resistor may be diminished in steps as the motor slows down. This practice is not usual except with the larger motors.

In the case of the adjustable speed motor care must be exercised not to brake rapidly from a weak field and high speed. If the field is rapidly strengthened at the same instant that the armature is shorted through the braking resistor,

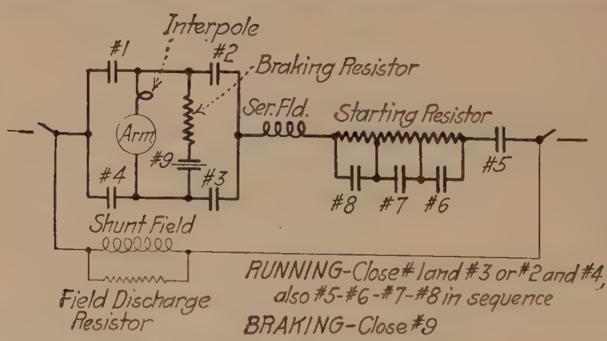


FIG. 279.—Principal connections of reversing dynamic braking controller for compound-wound motor.

excessive voltage and current will obviously result. This occurrence is prevented in some magnetic controllers by a relay which prevents strengthening the field faster than the braking current flow permits.

If the control of a shunt- or compound-wound motor is arranged for dynamic braking on the "off" position of the controller, it is necessary that the shunt fields be energized with the controller in this position. In many cases, the fields of a motor will overheat if left continuously in circuit, particularly without the fanning action of the armature. To avoid this difficulty, a resistor is sometimes cut into the shunt field circuit on the "off" position. This reduces the heating but also reduces the braking torque. A relay may be used to cut off the field

after the braking period, this being in the nature of a complication. If distinct braking points are provided on the controller besides an "off" position, all is well if the operator does not leave the controller on a "brake" position. Many controllers provide "drift" points, as braking may not be always desired.

The shunt field is generally energized from the line but arrangement may be made to energize the field from the self-generated voltage in the armature. In such case the excitation drops off as the motor decelerates but the sluggishness of the fields assists in maintaining the flux and braking torque. It should be noted that, in the case of a motor which reverses, the counter-voltage, for one direction of rotation, is from A_1 to A_2 and, for the other direction, from A_2 to A_1. In order that the shunt field may be excited in the same sense, in either case, the connections between armature and field must be suitably interchanged. If F_1 is always connected to A_1 and F_2 to A_2, in the braking position, the braking will be effective for one direction of rotation but, in the other direction, the armature voltage will send reverse current through the field and kill the flux. It has been found, however, that even in this case some braking effect may be had due to the sluggishness of the fields.

Dynamic Braking with Series Motors.—Dynamic braking cannot be obtained with a series motor in the same way as with a shunt- or compound-wound motor. Dynamic braking to stop a series motor can be obtained, however, by disconnecting the motor from the line and reconnecting armature and field in series with resistors. The result is a severe cumulative braking action and the armature current tends to reach a high value if not properly restricted by resistance. The braking current, flowing through the series winding, serves to supply the field flux. The braking voltage builds up from residual and is thus cumulative, as already mentioned. It should be noted that if the armature and series field were disconnected from the line intact and shorted through resistors, the direction of flow of braking current through the series field would be opposite to its normal flow. The series field would immediately kill the residual magnetism and no braking would result. It is necessary to reverse the series field (or armature) so that the braking current will flow through the series winding in the same direc-

tion as the motor current, thus building up on the residual. Figure 280 shows one scheme of connections used for this purpose, this arrangement being one sometimes used for the trolley motion control of coal and ore bridges.

Dynamic braking is more simply accomplished with shunt- or compound-wound motors. Dynamic braking with the series motor has one advantage, however, in that more effective

Scheme of Main Connections

Switch	Forward							Off	Reverse						
	Power			Brake					Brake				Power		
	3	2	1	1	2	3	4		4	3	2	1	1	2	3
1	O	O	O						O	O	O	O			
2				O	O	O	O						O	O	O
3				O	O	O	O						O	O	O
4	O	O	O						O	O	O	O			
5	O	O	O										O	O	O
6				O	O	O	O		O	O	O	O			
7	NOTE											NOTE			
8	O	O			O	O	O		O	O	O			O	O
9	O					O	O		O	O					O
10	O						O		O						O

Closes for Slow-down on Overtravel

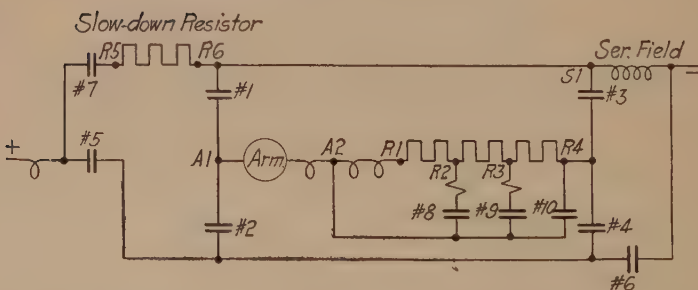
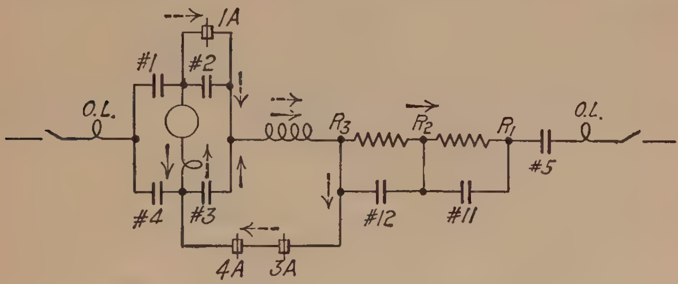


FIG. 280.—Connections of series motor with dynamic braking control.

braking is obtained independently of an outside source of power necessary to excite the fields. Partly for this reason dynamic braking with the series motor is well adapted for the man-trolley travel control of a coal or ore bridge, although the series motor is to be preferred for this application mainly because of its suitable characteristics and its requirement of a minimum of conductors. It should be noted, in this connection, that dynamic braking is effective in case of failure of power only in

case the contactors in the braking circuit are not dependent upon the power supply to remain closed.

If it is desired to obtain dynamic braking in one direction of travel only, the series motor can be readily applied. Figure 281 shows the connections of a controller arranged for this purpose. Contactors 1*A*, 3*A* and 4*A* are gravity-closed, being back con-



	Forward			Off	Reverse		
Step	3	2	1		1	2	3
Contactor 1	O	O	O				
2					O	O	O
3	O	O	O				
4					O	O	O
5	O	O	O		O	O	O
11	O	O				O	O
12	O						O
1A				O	O	O	O
3A				O	O	O	O
4A	O	O	O	O			

Dynamic braking obtained from forward rotation only. Solid lines indicate current flow for forward rotation. Dotted lines indicate current flow when braking from forward rotation

FIG. 281.—Connections for reversing controller for series motor, giving dynamic braking in one direction.

tacts of contactors 1, 3 and 4, respectively. Thus the braking effect is obtained in case of failure of outside power. This control has been successfully applied to hot metal mixers to give braking effect when tilting to pour. It may be also applied to a steel mill screw-down to give braking action when screwing downwards.

Braking by Bucking Motors.—Dynamic braking is sometimes employed in railway service and elsewhere, either with or without intent, through the action of two series motors, connected in parallel. Under certain conditions such motors will act in series to set up a braking current through their local cir-

cuit. This action may be best considered with the aid of the simplified diagrams in Fig. 282*a*, *b*, *c*. Figure 282*a* shows two series motors in railway service, connected in series. The arrows indicate the direction of current flow and armature counter-voltage. If the reverse switch be thrown and the main drum turned to a parallel position, the conditions are as shown

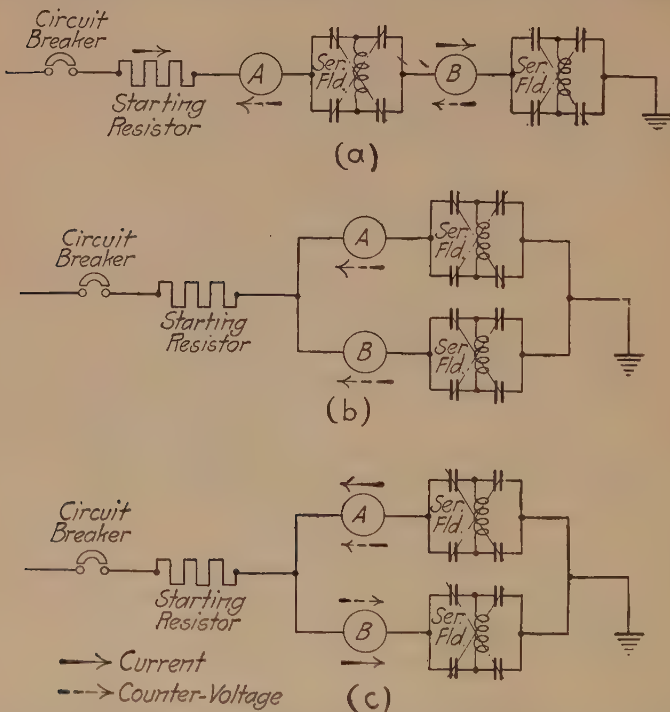


FIG. 282.—Connections showing bucking of two series motors connected in parallel.

in Fig. 282*b*. This is but a momentary condition, however. Due to the slight inherent differences which always exist between any two motors of the same design, one motor will have a higher residual magnetism than the other. Thus motor (*A*) will build up voltage more rapidly than the other (*B*). It will then tend to circulate current through motor *B*, overcoming the residual voltage of the latter, and will reverse the field and consequently

the voltage generated by motor *B*. A local current then flows, as indicated in Fig. 282*c*. This braking current, flowing through the two motors in series, short-circuited, is likely to reach

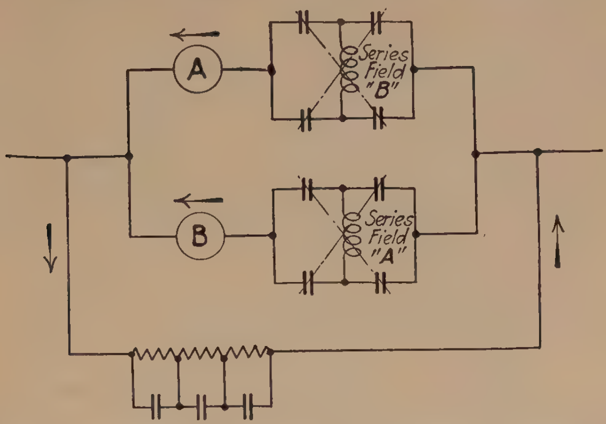


FIG. 283.—Connections for rheostatic braking used in railway service.

severe values and may result in flashing or damage due to the mechanical shock of the sudden torque. This procedure should therefore be restricted, in railway service, to emergency con-

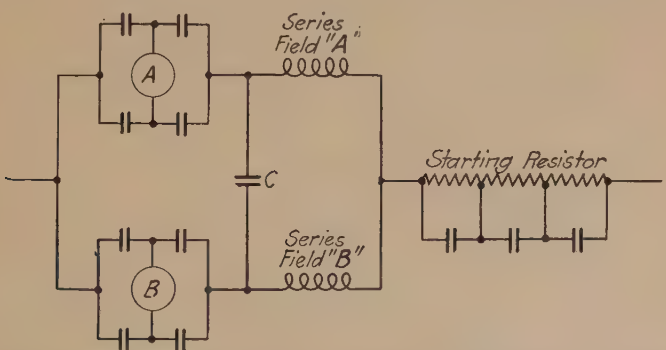


FIG. 284.—Two series motors in parallel, with equalizer connection. Contactor *C* is open while motoring and closed while braking.

ditions. However, this condition may and sometimes does arise in other applications where two motors are paralleled, using a single set of starting resistors. Where two sets of start-

ing resistors are employed, one for each motor, as indicated in Fig. 275, Chap. XXI, the local series circuit includes the starting resistors which suffice to prevent or restrict the flow of current in this local circuit. It is possible to prevent the flow of circulating current in a closed loop caused by reversing two series motors connected in parallel by interchanging the series fields as indicated in Fig. 283. With this arrangement any unbalancing is quickly corrected. Sometimes an equalizer connection is used, connecting the armature-series-field junction points of the two motors, for like purpose. This arrangement is indicated in Fig. 284. It is simpler than that of Fig. 283 but not so positive in corrective action.

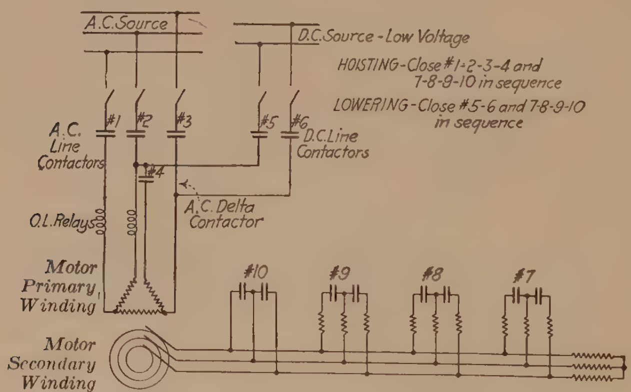


FIG. 285.—Dynamic braking with induction motor.

Dynamic Braking with the Induction Motor.—The alternating-current induction motor is not inherently adapted for dynamic braking service. The load current and magnetizing current flow through the same winding and from a common source, and cannot be dissociated. Two schemes have been developed and applied for obtaining dynamic braking from induction motors. In both schemes direct current is applied to the primary winding to create a fixed magnetic field. The rotor conductors, cutting this field, generate voltage and circulate current in the secondary circuit. The braking torque may be governed by the amount of direct current in the primary and by the resistance of the secondary circuit. The amount of

direct current introduced into the primary is in general magnitude comparable with the full-load alternating current. The direct-current supply must be at low voltage because only the resistance of the primary windings is involved. In one scheme the direct current is obtained from a small motor generator set, which in turn is excited from an auxiliary exciter. In another scheme the direct current is obtained from a generator which is

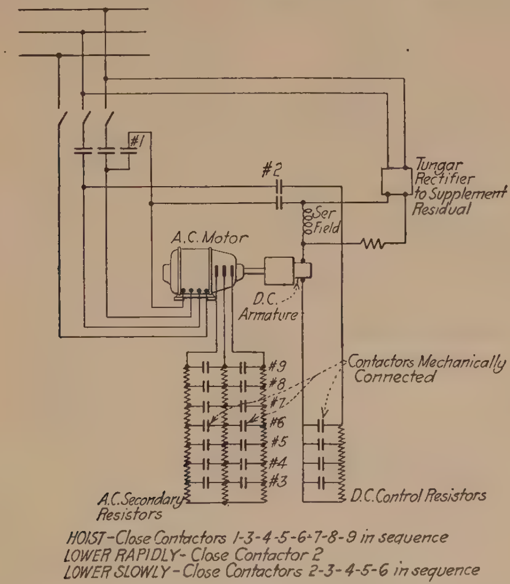


FIG. 286.—Dynamic braking with induction motor and direct connected direct-current generator.

mounted on a common shaft with the induction motor. This unit has its field winding excited from a tungar rectifier. The latter scheme offers some advantage in that the auxiliary direct-current unit assists in braking, the braking current is automatically adapted to the load and the direct-current excitation automatically ceases when the motor stops. The principal connections for these two systems of braking are shown in Figs. 285 and 286.

Direct current may be applied to the stator windings in several ways, as indicated in Fig. 287 (*a*), (*b*), (*c*), (*d*), (*e*), (*f*),

(*g*), (*h*). The connections shown in (*c*), (*f*) and (*h*) are a little more effective as the entire stator winding is excited uniformly and the adjacent phase groups for each pole of the motor all have the same polarity. The other connections are more simple but are slightly less desirable from the viewpoint of field form and power requirement. The connections shown in (*a*) and (*d*) are most often used.

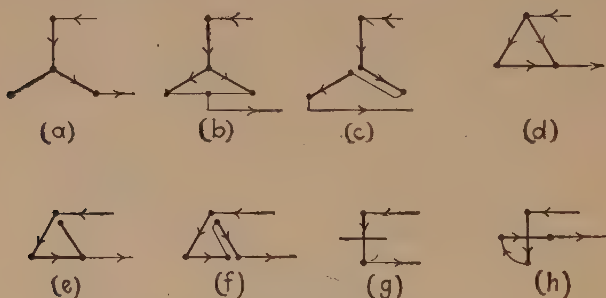


FIG. 287.—Methods of applying direct-current to the stator of an induction motor to secure dynamic braking.

In Fig. 288 are shown the dynamic braking curves of a 700 hp., 3-phase, 60-cycle, 220-volt, 514-r.p.m. wound-rotor induction motor with constant direct-current excitation of 230 amperes and with three different values of secondary resistance. It will be noted that the dynamic braking characteristics are similar to the speed-torque curves of the motor except that they are upside down. This is due to the fact that, in dynamic braking, the rotor revolves in a stationary magnetic field, while in the ordinary operation as a motor the rotor revolves in a magnetic field which is revolving at synchronous speed.

The torques obtained by dynamic braking of induction motors are somewhat less than can be obtained by plugging but a torque of 150 per cent full-load value can be readily developed. The secondary voltage in dynamic braking is lower than that resulting from plugging. Too strong direct-current excitation is undesirable, partly because the interruption of a portion of the exciting circuit might lead to damage through unbalanced magnetic pull. Dynamic braking of

induction motors is economical of power, and affords smooth and flexible control. Although not in extensive use, it is well adapted for some applications.

Dynamic Braking with the Synchronous Motor.—As mentioned in Chap. VII, it is possible to obtain dynamic braking with the synchronous motor. This is accomplished by disconnecting the primary leads from the line, while the motor is running, and then short-circuiting the primary through suit-

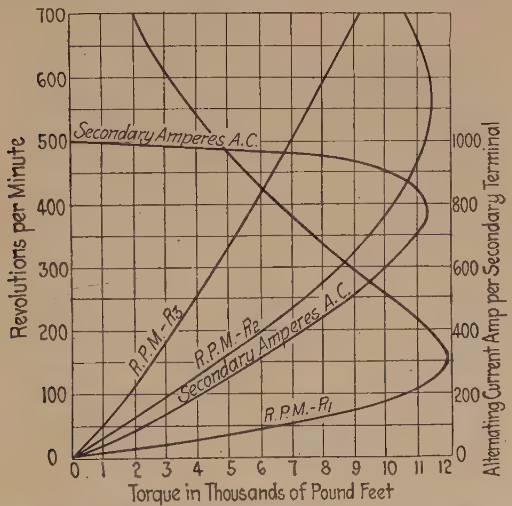


FIG. 288.—Dynamic braking curves of a 700 H.P. 3-phase 60-cycle 220-volt wound-rotor induction motor with constant direct-current excitation.

able resistors. The rotating fields generate voltage in the primary, resulting in a braking current flowing through the primary windings and the external short-circuiting resistors. The field excitation is reduced to restrict the generated voltage and braking current. This arrangement has been used effectively for obtaining a quick emergency stop of motors driving rubber mill lines.

Braking for a Slow-down.—If a direct-current motor, running at full speed, have its starting resistors suddenly inserted in circuit there will be little or no electrical braking effect. The driving torque will, of course, fall off and friction or load will slow down the machine, opposed by inertia. In case the load

is overhauling the motor will speed up. Dynamic braking can be employed to obtain a definite slow-down from full speed to a fixed lower speed, by connecting resistors in parallel with the armature, which is connected in series with the starting resistors. The voltage drop in the series resistors reduces the voltage at the motor terminals to a value lower than the counter-

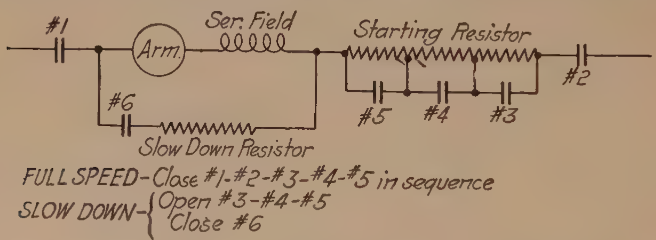


FIG. 289.—Series motor with slow-down resistors around entire motor.

voltage. Current is then forced by the armature through the parallel resistors in a direction to cause braking action until the armature slows down and the counter-voltage drops off. The motor will quickly come to a speed corresponding to the reduced terminal voltage, the exact speed depending upon the values of series and parallel resistance and upon the load.

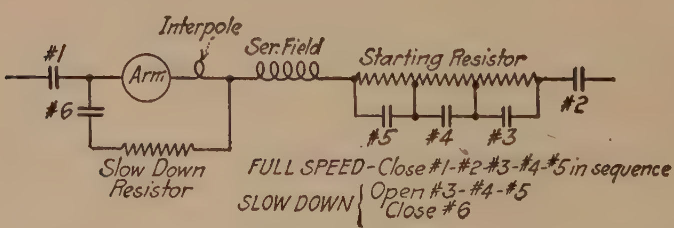


FIG. 290.—Series motor with slow-down resistors around the armature and interpole only.

This action is obtained, with a shunt-wound motor, by shunting the armature with the parallel resistors. With a series motor, the armature may be shunted by the resistors or the entire motor may be shunted (see Figs. 289, 290). Shunting the armature alone causes a more pronounced braking action as the series field flux is well maintained or may be

strengthened (depending on relative resistance values). Shunting the entire motor causes a less severe and less effective braking action. The low speed obtained with shunted armature is fairly constant, with either shunt or series motor, but falls off somewhat under load. The regulation depends upon the series and shunt resistance values. Figure 291 shows the speed-current curves for a skip-hoist motor, compound-wound. Two slow-down points are shown. The motor is a simple shunt motor while running, having the characteristic curve 1.

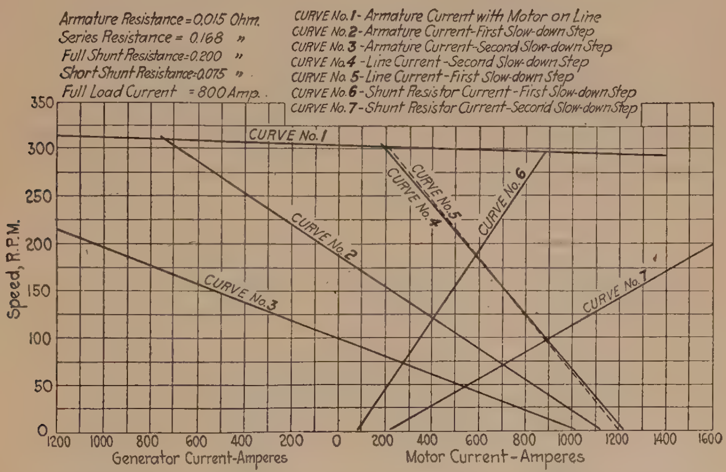


FIG. 291.—Speed-current curves of a motor with a shunted armature.

On the first slow-down point the series field winding is introduced, the starting resistor connected in series and the armature shunted with a resistor. On the second slow-down point the shunting resistor is reduced. It should be noted that, if complete slow-down were attempted in one step, there would be a very high initial rush of braking current, corresponding to full speed (300 r.p.m.) on curve 3, and braking would be severe. It should also be noted that the torque developed on the slow-speed points is relatively low and the motor may stall if the armature is too heavily shunted.

Slow-down with the Induction Motor.—The wound-rotor induction motor is similar to the direct-current motor in that a

definite slow-down cannot be obtained by insertion of resistors in either primary or secondary circuits. A slower speed will eventually result but will not be attained through any marked braking action developed by the motor. The multispeed induction motor is applied, however, to obtain a definite slow-down. The motor is run on its high-speed winding, the low-speed winding being utilized for the slow speed. At the instant of change-over, the rotor is revolving at a speed exceeding the synchronous speed for the low-speed winding. The motor

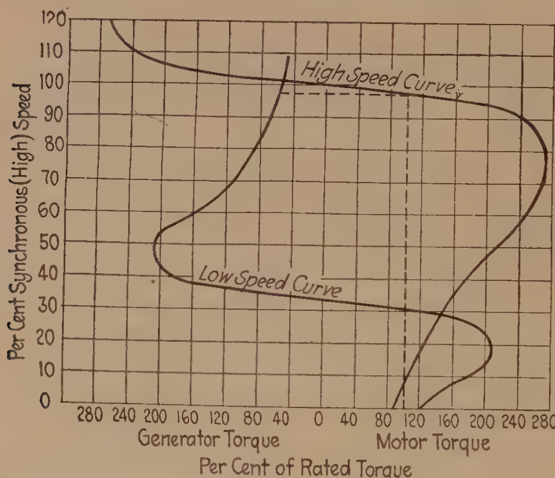


FIG. 292.—Speed characteristics of a two-speed (3 to 1) induction motor, showing action at time of transfer.

acts temporarily as an induction generator with reversed torque. The action may be more evident by inspection of the curves in Fig. 292. It will be noted that the braking current at the instant of change-over may be very high. In some cases external resistors are inserted in the secondary circuit of a wound-rotor motor to minimize this effect. In some cases a high resistance cage motor is employed. This has a less flat characteristic and the current inrush is lower. Primary resistance is also used with some cage motors.

Dynamic Lowering for Crane-hoist Duty.—A somewhat special case of dynamic braking is employed in crane-hoist

service. This is explained in Chap. XI, page 254, and a typical controller of this kind is discussed in Chap. XV, page 344.

Dynamic Braking Applications.—A word may be in order concerning the uses and advantages of dynamic braking. These have been already suggested. Perhaps the most extensive application is in crane and hoist service for lowering. Elevators employ regenerative braking for restraining overhauling loads and dynamic braking both for slow-down and for stopping. Skip-hoist control is similar. Machine tools often use dynamic braking to obtain a quick stop. Some reversing planers use it to bring the platen to a stop prior to reversing. Dynamic braking is used extensively on steel mill auxiliary drives, such as the screw-down, to obtain a quick stop. It is used on ore and coal bridges for lowering the bucket and also for stopping the man trolley. It is used on the ingot buggy to obtain a slow-down. There are many other less general and less conspicuous applications.

Advantages of Dynamic Braking.—The advantages of dynamic braking are many. It has proven superior to mechanical braking on cranes and hoists. The principal advantages, here as elsewhere, are the nicely graduated control and the freedom from mechanical maintenance. The upkeep of friction brakes used for retarding or stopping is likely to be difficult and expensive. With dynamic braking most of the heat is dissipated in resistors situated apart from the motor. A brake on the motor shaft may transmit heat to the motor to a serious extent. Dynamic braking is easily adjustable and maintains its adjustment. Friction brakes require frequent adjustment and are affected by water and oil. Dynamic braking is quicker in action as most brakes have an appreciable time lag. Dynamic braking is sometimes used and supplemented by mechanical brakes. The dynamic braking reduces the speed to a point where this method of braking becomes ineffective. The mechanical brake then stops the motor.

Braking Energy.—This topic would not be complete without considering the work which must be done in stopping a motor and its driven load. When the driving power is removed and braking applied the inertia of the motor and moving machinery tends to continue the motion. It is necessary, in

braking, to dissipate the kinetic energy stored in these parts.

The energy stored in the motor armature or rotor is E_A.

$$E_A = \frac{Wr^2 \times \text{R.P.M.}^2_A}{5870} \text{ ft.-lbs.,}$$

where Wr^2 = moment of inertia of the armature, weight × radius of gyration^2;
R.P.M.$_A$ = rotative speed of armature.

The energy stored in the rotating machine parts, computed at any selected shaft, is E_m.

$$E_m = \frac{W_m R^2_m \times \text{R.P.M.}^2_m}{5870} \text{ ft.-lbs.,}$$

where W_m = weight of revolving members, lbs.;
R_m = radius of gyration members, ft.;
R.P.M.$_m$ = rev. per min. of selected shaft.

The energy stored in parts having linear movement may be determined by considering same as concentrated at wheel rim or drum periphery, as the case may be, or by considering linear forces. For instance, in a hoist, the energy stored in the moving suspended load is E_H.

$$E_H = \frac{W_H}{64.32} \times \left(\frac{V}{60}\right)^2 \text{ ft.-lbs.,}$$

where W_H = weight of all parts in linear motion, lbs.;
V = linear velocity, ft. per min.

The work done by or against gravity on the unbalanced portion of the suspended load, as in the case of a hoist, is E_G.

$$E_G = \frac{W_u V t}{120} \text{ ft.-lbs.,}$$

where W_u = unbalanced weight, lbs.;
t = time to stop, seconds.

The net or total energy of the load, to be absorbed by the motor or brake, is E_N.

$$E_N = \frac{W_H V^2}{230{,}000} \pm \frac{W_u V t}{120} \text{ ft.-lbs.}$$

Use + for stop while lowering.

Use − for stop while hoisting.

This is in addition to the kinetic energy of the motor armature and revolving parts of the hoist.

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CHAPTER XXIV

ELECTRIC BRAKES

An electric brake is a friction grip which is set by mechanical means and released electrically. Some brakes are set by gravity through the medium of a weight attached to a lever arm, others are set by springs. Release is ordinarily accomplished by an electric magnet or solenoid, but a small motor is sometimes employed. Most brakes are applied to an extension to the armature shaft as being the most effective point.

Functions of a Brake.—The function of an electric brake may be either to retard and stop a motor and machine, to hold a machine at rest against a force or both to stop and to hold. A brake must be dependable because, if it fails, life may be jeopardized or property seriously damaged. It must, therefore, have a high safety factor.

Types of Brakes.—Brakes may be classified according to their mechanical design. The common types are the band brake, the disc brake and the shoe type or post type brake. Brakes may also be classified according to their use on direct-current or alternating-current systems.

The Band Brake.—The band brake is a familiar type, consisting of a flexible band encircling the brake wheel. This band is lined with a woven friction material or with wood or composition friction blocks. The band is usually anchored at one end. The other end is drawn tight by a weight or spring which, in turn, is released by the solenoid. The band brake is a simple type. It has the advantage of large friction area as nearly the entire wheel circumference is encircled. It serves very well as a holding brake particularly against a force always in one direction. A band brake, as ordinarily applied, exerts more torque in the wrapping than in the unwrapping direction of rotation, the latter being one-third to one-half the former. However, some band brakes are so applied as to give nearly the

same braking effort in both directions of travel. A band brake causes a side thrust to be exerted on the shaft as the pull is largely in one direction. It is somewhat difficult to maintain clearance at all points around the brake wheel due to slight eccentricity and irregularity in the band, hence the opening movement must be considerable. Band brakes are commonly operated by solenoids having a fairly long travel. These solenoids may be actuated by either direct or alternating current.

The Disc Brake.—The disc type brake consists of a series of non-rotable plates or stages alternating with a series of

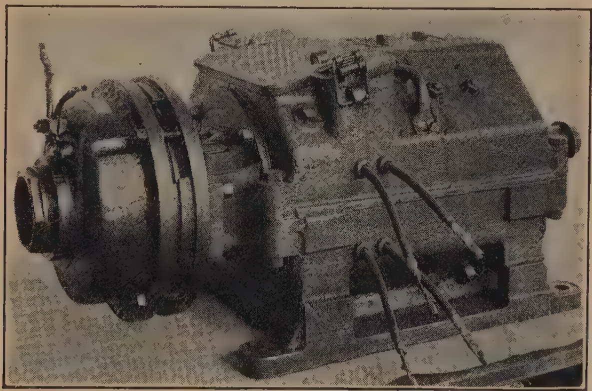

FIG. 293.—Disc brake attached to crane motor.

rotating plates. The stationary plates are machined surfaces. The rotating plates are loosely keyed to a hub mounted on or connected to the motor shaft. They are lined on both sides with friction material. The stationary and rotating plates are pressed together by a spring and are released and separated by a magnet. Figure 293 shows a brake of this type attached directly to a crane motor.

The principal advantages of the disc type of brake are its compact construction, its relatively light weight and its quick action. This type of brake requires very little room perpendicular to the shaft and little headroom. It has little inertia due to the light weight of its revolving parts. It has a large wearing surface area. It is at a disadvantage in that the

brake must be removed or dismantled in removing an armature. It is a little more difficult of alignment. It cannot readily be released by hand. The friction surfaces are enclosed, are somewhat inaccessible for inspection or repair and the heat-dissipating ability is restricted. Ventilation is provided to minimize this difficulty. The enclosure of the friction surfaces protects them from oil and from the weather. The disc brake can be mounted on the end of a shaft only. It cannot be well adapted for alternating current.

The Shoe Brake.—The shoe type brake is probably the most commonly used. It consists of a brake wheel and two shoes which are attached to levers. The shoes are made to clamp the wheel, either by weights or springs acting on the levers. In some types there is a more or less complicated linkage of levers. The shoes are released either by a solenoid or by a magnet acting through the levers.

The shoe type brake is both rugged and accessible. It introduces no end thrust or side thrust. It is usually attached to the armature shaft extension but may be attached to a central portion of a shaft. This type of brake may be arranged to permit easy removal of the armature. Shoe brakes are commonly 30 to 40 per cent heavier than band or disc types. They require a comparatively powerful solenoid. They have a minimum area of wearing surface. The friction surfaces are exposed to the weather. Some designs are rather bulky and require considerable space alongside and headroom above the motor.

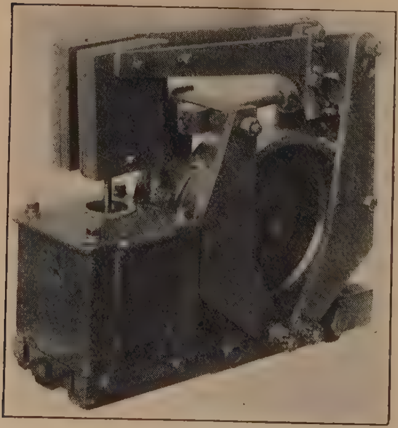

FIG. 294.—Shoe brake, gravity set and solenoid released.

There are many designs of shoe type brakes, differing considerably in their principal features. Figure 294 shows a

brake which is set by gravity and released by a solenoid. This type of brake is well adapted for use with a dash pot. Cut-out devices mentioned later may be readily applied. The coil is enclosed and fully protected.

There is considerable inertia in the moving members in a gravity-actuated brake, tending to delay initial movement and tending to cause rather sudden clamping action. In any solenoid brake there is some magnetic lag and there may be friction between the plunger and the bore of the solenoid.

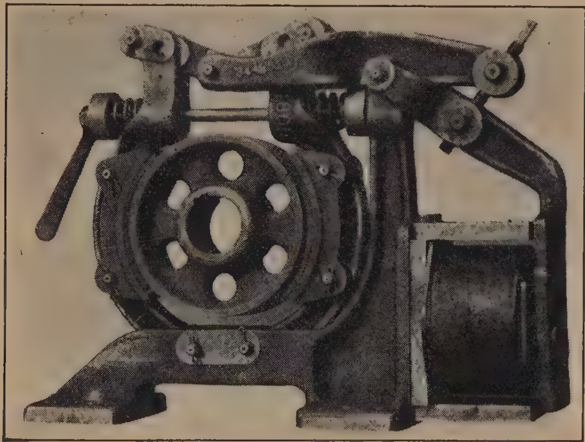

FIG. 295.—Shoe brake, spring set and magnet released.

Figure 295 shows a shoe brake which is actuated by springs, a magnet being used instead of a solenoid.

A large number of levers in a brake mechanism is undesirable because of complexity and there is more or less wear at the hinge pins, depending upon the amount of pressure and movement. This leads to friction and lost motion. Figure 296 shows a simple shoe type brake employing a minimum of parts. The brake is set by a spring enclosed within the magnet housing. It is released by a large, short-stroke magnet. This brake is exceptionally compact, and requires little head-room. The short stroke affords quick action and the comparative absence of inertia eliminates shock on setting or hammer on release. The brake can be easily dismantled for removal

of the armature without affecting its adjustment. The magnet coil is enclosed and protected. This brake is adapted for direct current only.

Series and Shunt Windings for Brakes.—The majority of direct-current brakes are wound with relatively few turns of heavy wire and arranged for connection in series with the motor. The most obvious reason lies in the fact that a coil thus connected is automatically de-energized and the brake released when the current is shut off. There are other contributing causes for preference of a series brake where applicable. In

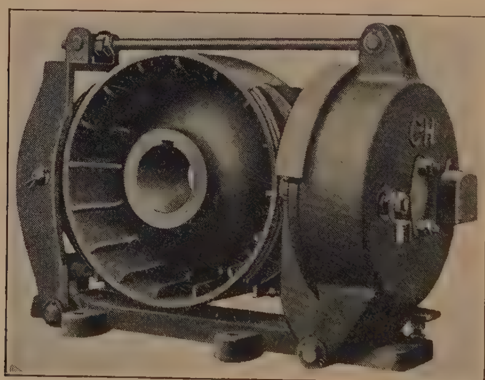

Fig. 296.—Shoe brake, spring set and magnet released.

the case of a crane, an extra trolley bar and collector would be required if a shunt brake were used. With a series brake there is definite assurance that when the brake is released the motor has current to hold the load. A shunt brake might be released even with the armature circuit open and no holding torque developed. The coil of a series brake contains fewer turns of relatively large wire and is therefore more rugged and dependable. The series-wound solenoid acts more quickly than the shunt coil in releasing and setting the brake.

On the other hand, there are many applications where the use of the shunt-wound brake is necessary or preferable. In elevator service and mine-hoist service the armature current may pass through zero and flow in either direction, depending upon whether the motor hoists or retards. A series brake

could not be held open. In the case of a crane hoist, the brake is ordinarily connected in series with the series field in lowering. If a high lowering speed is desired it is necessary to weaken the series field to a point such that the current passed in this circuit would not hold open a series brake. Shunt brakes are therefore frequently used for the hoists of coal and ore bridges, skull crackers and similar service. It is often desirable to have a drift point on a control. Obviously this is feasible with a shunt brake only as this may be maintained energized. Crane bridges are sometimes thus equipped, also lift bridges. The shunt brake also has some advantage in that its energizing circuit may be handled by a small contactor which may be interlocked with protective features. The advantage of the series brake lies in simplicity of action. The advantage of the shunt brake lies in flexibility of application.

The point has been raised that a shunt-wound brake tends to be more sluggish than a series brake. This is due to the inductance of the shunt coil which retards the building up and dying out of the flux. In order to alleviate this condition some shunt coils, particularly for the larger brakes, are sometimes wound for half voltage and connected in series with resistance. This permits a high current inrush and gives quick release. In some cases the sluggish action is desirable. Compound-wound brakes are not uncommon. The series coil is usually in circuit for a short period to give quick release. It is then short-circuited by the control, leaving a comparatively light shunt winding to hold the brake released.

Alternating-current Brakes.—The alternating-current magnet is not as well adapted for brake duty as the direct-current magnet. A relatively bulky laminated construction is necessary to limit iron losses and heating. Both single-phase and polyphase long-stroke magnets and polyphase short-stroke magnets are used. Alternating-current magnets are permitted to seal. It is difficult to keep such a magnet quiet, particularly if of the single-phase type. The current in a single-phase coil passes through zero every cycle. Shading coils are employed to carry the magnetism over these periods. However, some tendency to chattering is liable. Long-stroke magnets tend to slam in closing. Dash pots are sometimes

used to minimize this effect. In some cases the entire magnet is immersed in oil to minimize chattering and noise and also to damp the action.

Alternating-current brake solenoids are all shunt-connected. The pull of the solenoid varies decidedly with the voltage. Taps are sometimes supplied so that the coil may be adapted to conditions. The current in a direct-current coil depends on resistance and is independent of the air gap. The current in an alternating-current coil is limited by impedance, mostly reactance. The longer the air gap the less the flux and the lower the reactance. The current is a minimum when the air

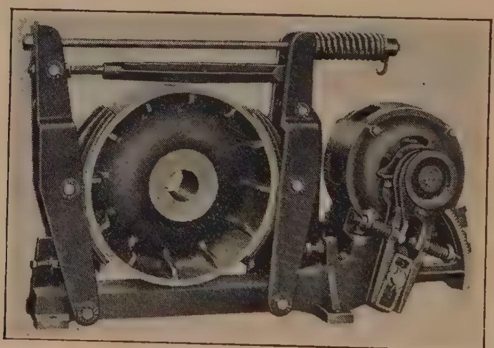

FIG. 297.—Spring set, motor released brake for alternating-current service.

gap is closed and is much higher when the gap is open. When voltage is applied a high current inrush occurs, the current falling off as the air gap closes. In operating an alternating-current solenoid it is necessary to see that the moving core pulls up promptly, else the current will be excessive and will probably burn out the coil.

Figure 297 shows an alternating-current shoe type brake in which a motor is employed instead of a solenoid for releasing. The brake is set by a spring. The motor drives through a pinion and toothed sector to which a lever is attached. The motor exerts torque to release and hold open the brake. The motor is a special high resistance cage type induction motor designed to withstand stalling. The motor is equipped with

a combination slip gear and mechanical brake device which cushions its action. This type of brake is quiet in action as vibration and chattering are eliminated. The shoes are applied without shock and released without pounding. No dash pot is required. There is no initial current inrush and possible coil burnouts are avoided.

Brake Adjustments.—There are usually three adjustments to a solenoid or magnet-operated brake. These are: adjustment for shoe clearance, for braking intensity and for air gap. It is necessary to adjust the shoes for equal clearance and equal braking effect without side thrust. The braking intensity is adjusted by change in the amount or leverage of the weights, by changes in the lever linkage or by adjustment of the compression of the springs, as the case may be. It is desirable to maintain a definite air gap at the solenoid or magnet in order to obtain the required pull. The air gap should be the minimum amount which will give sufficient movement to release the wheel fully. The proper adjustment of the magnet, on direct current, affords the strongest obtainable magnet pull, thus permitting maximum braking intensity adjustment and giving prompt and definite action. In the case of alternating current, proper adjustment helps to prevent excessive current inrush due to wide air gap.

Avoidance of Shock.—It has been mentioned that some types of brakes are more sluggish in action than others. This is not always an undesirable feature. What is desired is prompt release without a hammer blow caused by sudden stoppage of the moving parts, together with prompt but gradual setting. Some brakes tend to grip suddenly and cause a shock to the load and the transmission gearing. It is evident that minimum inertia in the moving parts is desirable to these ends. In this respect the use of compression springs has advantage over weights. In some brakes either an air or oil dash pot is supplied to cushion the action, and prevent too sudden application. In a few cases, in connection with shunt-wound brakes, electrical means are employed to delay the action. This may be done by shunting the brake coil with a discharge resistor. The stored energy in the coil causes a current to flow through the discharge resistor when the coil circuit is opened.

This discharge current delays and cushions the setting of the brake. A short-circuited damping winding will have a similar effect. Totally enclosed "ironclad" solenoids have this effect to a limited extent due to the eddy currents in the iron when the magnetism is established or interrupted. The motor-released brake is damped to some extent by the inertia of the rotor of the small releasing motor.

Methods of Mounting.—Brakes are more commonly mounted separately on the motor bed plate. Frequently, however, they are attached to the motor. Motor-mounted brakes require finished pads on the motor and, in some cases, special parts for adaptation. Most crane and hoist motors are provided with brake pads. The advantage of motor-mounting lies in the self-contained unit with no alignment difficulties and no special base construction. The disadvantages are less firm and substantial construction and less easy dismantling. Motor-mounted brakes are usually of the disc type.

Rating of Brakes.—Brakes are rated in pound-feet of retarding torque which they will develop at the brake wheel shaft, as referred to revolving wheel condition. As the coefficient of static friction is higher, the holding torque is somewhat greater than the retarding torque. The holding torque is ordinarily about 110 per cent of the retarding torque. The retarding torque which a brake will develop depends materially upon the amount of weight or the extent to which it is "set up." This in turn depends upon the strength and ability of the solenoid or magnet to release. Where an intermittent duty coil is used, it may be worked harder and made more powerful. Therefore the brake may be set up tighter and its retarding torque rating increased.

It is evident that a brake retarding a given torque from high speed will dissipate more energy than one retarding the same torque at low speed. The ability of a brake to dissipate the mechanical energy which is converted into heat is one of its limitations. Brakes are therefore given a maximum horsepower rating which signifies the highest horsepower motor with which the brake may be expected, under average conditions, to function without undue heating and with reasonable shoe wear.

The coil of a series brake carries motor current and must be proportioned accordingly. Brakes are rated in the same manner as the motors with which they are used, the common ratings being on a 30-minute or 60-minute basis for intermittent duty and a continuous duty rating. The intermittent duty brakes will release on 40 per cent rated current. Continuous duty brakes will release on 80 per cent rated current. Series brakes, once released, will hold open down to about 10 per cent of rated current. It is desirable in crane-hoist dynamic lowering that the brake release on 40 per cent full-load current or less. The brake should open on the first point lowering.

Shunt-wound brakes are given either a continuous duty or an intermittent duty rating. The coils of some brakes are wound for less than rated voltage. The coil is connected across the line to release the brake. Movement of the brake members actuates a small switch which causes a resistor to be inserted in series with the brake coil. The reduced current is sufficient to hold the brake released but minimizes the coil heating.

Selection of Brake.—Brakes are selected on the basis of torque. The full-load torque of a motor may be determined by the formula:

$$T=\frac{5250\times \text{H.P.}}{\text{R.P.M.}},$$

where T = torque in lb.-ft.;
H.P. = full-load horsepower rating of motor;
R.P.M. = speed of brake wheel.

Ordinarily a brake is selected having a retarding torque equal to full-load motor torque. Sometimes a lesser torque will suffice and sometimes a higher torque, such as one and one-half times full-load torque, is thought desirable either to gain a very quick stop, to hold an occasional heavy load or to provide a safety factor, particularly as to adjustment and condition.

Where service is particularly severe or continuous, the heat-dissipating ability of the brake becomes a governing factor and it is necessary to select a brake on the basis of its limiting horsepower rating rather than its torque. The limiting temperature which lining materials will stand is about 200° C. It may be well, at this point, to state that hard lining materials

are desirable as they will retain adjustment better. Soft linings give more friction but they wear faster and compress.

For high speed work it is necessary to check the peripheral speed of the brake wheel.

Graduated Braking Effort.—The brakes which have been thus far described and discussed are of a type which are either fully set or fully released, as the case may be. There has been recently developed a brake for use on alternating current

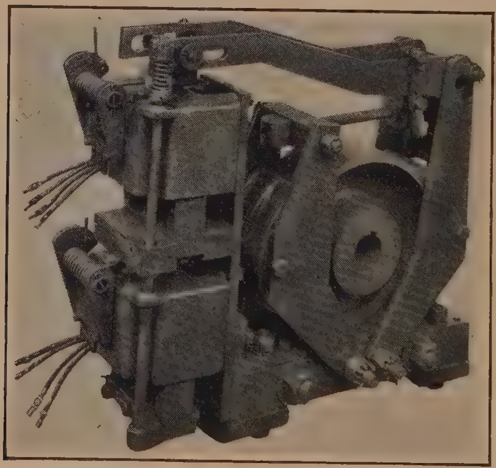

Fig. 298.—Alternating-current brake providing graduated braking effort.

which affords graduated braking. This brake is adapted for crane-hoist service.

It is similar in general construction to the ordinary shoe type solenoid brake. It has, however, two solenoids. One of these is connected across primary voltage and is energized only while hoisting. At standstill or when lowering, except on regenerative braking points, this solenoid is de-energized. The second solenoid is connected across a phase of the rotor of the motor. When both solenoids are de-energized, as at standstill, full braking torque is obtained. In hoisting, the two solenoids function together to release the brake. In lowering, the second solenoid governs. When this solenoid is energized, the braking torque is relieved in proportion. As this solenoid is across

rotor voltage the higher the lowering speed, the less the slip and the lower the rotor voltage, hence the greater the braking torque. The brake thus automatically adapts its effort toward controlling the speed. Figure 298 shows a brake of this type.

The three-phase short-stroke solenoid brake has also been used to give graduated braking effort. A reactor is inserted in series with the brake solenoids to give a partially energized condition, permitting the brake to close but preventing sealing and restricting the braking torque. If the reactance be gradually reduced, the brake may be gradually applied. This type of brake has been successfully employed in elevator service. It is apt to be noisy while the reactor is in circuit.

Applications.—Electric brakes find a wide field of application. Cranes, hoists and elevators are probably the greatest field. Steel mill auxiliaries often require brakes. Lift bridges are so equipped. There are many miscellaneous applications.

In closing it may be stated in general as more desirable practice to retard and stop loads electrically by dynamic braking and to utilize the friction brake largely for holding. This practice minimizes the wear on the brakes, decreases their maintenance and insures with greater certainty their good condition for their important holding duty. There are, of course, many exceptions where this added complication may not be warranted.

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